中華民國地質學會與中華民國地球物理學會 113 年暨學術研討會

摘要集

目錄

Speciation of various elements on an asteroid Ryugu to estaimte aqueous environment in the parent body using a key material, smectite

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The parent body of the C-type asteroid Ryuguu is thought to have been rich in volatile elements and abundant in liquid water, making it an important research target for the origin of water and organic matter on Earth. The water caused various alteration in the surrounding minerals, resulting in layered silicates such as smectite (saponite) and serpentinite being the main constituent minerals of the Ryugu (Nakamura et al., 2023). In this process, the organic matter of the Ryuguu parent body also underwent chemical reactions and a wide variety of organic matter was synthesised (Naraoka et al., 2023). It is particularly important to obtain information on the water environment during the aqueous alteration, as the products of chemical reactions of organic matter in water depend on the pH and redox potential (Eh) of the water. In this study, speciation of various elements was carried out using scanning transmission X-ray microscopy (STXM) and bulk X-ray absorption near-edge structure (XANES) related to the aqueous environment in the Ryugu parent body. The speication of these elements in smectite (saponite) is particularly important, since the Fe oxidaiton state and chemical composition within the interlayer of the saponite can indciate Eh-pH condition of the Ryugu water.

The Fe(II)/Fe(III) ratio in the octahedral structure of saponite was conducted by STXM. Based on our laboratory experiments, dithionite reduction of natural Fe-bering saponite corresponding to Eh range from -0.47 to -0.66 (V) at pH = 7 shows the Fe(II)/Fe_{total} ratio around 0.55. The incomplete reduction by dithionite reveals that Fe(II)-bering saponite is a strong reductant. Assuming that the relationship between the Fe(II)/Fe_{total} ratio and Eh of nontronite in Gorski et al. (2013) is similar to that of saponite, the Fe(II) /Fe_{total} ratio greater than 0.68 measured by STXM indicates that the Eh was less than -0.45 (V).

On the other hand, because saponite has a negative charge in its layered structure, cations from the aqueous phase are adsorbed between the saponite layers during aqueous alteration. In this case, as shown by Fukushi et al. (2019), which cations are retained in the interlayer depends on the concentration of various cations in the coexisting aqueous phase and the selectivity coefficient K. Therefore, the cation composition in the water layer at the time of aqueous alteration can be estimated from the interlayer cation ratio determined by various analytical methods. In this process, speciation of Na, K, and Ca were conduted to obtain their fractions retained in the interlayer. The comparison of the Al content in saponite enables us to estimate the Mg content in the interlayer. Contents of these cations with assumptions of dissolved silica etc. were used to constraint an Eh-pH diagram of Mg. We have estimated pH range that can explain the presence of both saponite and dolomite, which are widely distributed in the altered crust in the Ryugu particles. The pH range estimated by the method was pH from 9 to 11. Although the range is somewhat wide, the range is consistent with the results suggested in Nakamura et al. (2022). The cmbination of Eh around -0.45 (V) and the alkaline pH range estimated above showed that the water was highly reducing, which reveals that H_2 and CH_4 were present in the Ryugu water if we assume the equilibrium condition. Such an alkaline condition is suitable for the polymerisation of amino acids and abiotic synthesis of nucleobases (Kitadai and Maruyama, 2018).

In the presentation, the importance of analysis of smectite will be also highlighted, since the cation adsorption on the smectite is also important in enviromental chemistry and resource chemistry in addition to the cosmochemical appliation.

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Ionospheric GNSS geophysical applications

電離層全球導航衛星系統之地球物理應用

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The total electron content (TEC) derived by ground- and space-based GNSS (global navigation satellite system, GPS/GLONASS/Galieo/DeiDou) receivers are used to study ionospheric disturbances induced by typhoons, volcano eruptions, seismic waves, and tsunamis. On the other hand, global ionosphere maps are employed to find characteristics of temporal SIPs (seismo-ionospheric precursors) of TECs associated with large earthquakes at a certain location. The SIP characteristics are further applied to detect possible SIPs of forthcoming large earthquakes at the location, while spatial analyses are used to confirm the SIPs being detected. Concurrent in-situ plasma measurements of multi-satellites, such as DMSP, FORMOSAT-5, FORMOSAT-7/COSMIC-2, etc., find causal mechanisms of the observed SIPs.

SeisBlueAI地震資料處理平台開發理念

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摘　要

微震監測技術可提供極為詳細的地震分布數據，是提升地震數據分析解析度的重要手段。然而，過往因人工處理成本過高，常需數月時間才能獲得可觀的成果。為解決此一問題，目前國內外已有眾多案例透過 AI 模型加速地震事件的偵測工作，然而這些開放原始碼的案例多僅證明其方法的可行性，對一般使用者而言較不友善。因此，我們自主開發了 SeisBlue 平台，為了降低研究人員運用 AI 模型的門檻，使之成為一種穩定且可靠的技術。

SeisBlue 平台提供五項主要功能：資料前處理、波相到時挑選、波相關聯定位、震源機制分析與資料視覺化。在開發過程中，我們特別重視多項非功能性設計，包括資料流程的模組化、模型的版本控制、系統效能優化以及平台的可擴充性，以確保系統的可靠性與使用者的便利性。

SeisBlue 平台已在多項研究計畫中投入使用，包括寶來地熱探勘計畫、0918 池上關山 餘震序列速報等，並取得了相當正面的成效。

關鍵字：地震觀測、人工智慧、軟體工程、SeisBlue

Keywords: Seismicity Monitoring, AI, Software Engineering, SeisBlue

Title: Improved uranium isotopic measurement in carbonates using MC-ICP-MS
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Abstract:
U-series dating is a crucial method for determining the ages of late Pleistocene carbonates. Achieving precise measurements of the $^{234}U/^{238}U$ ratio at permil to sub-permil levels presents a significant challenge due to the four-order abundance differences between these isotopes. This difficulty arises from the interference of the tailing background from the high-energy distribution of the ^{238}U ion beam after plasma-induced ionization. Here we present two uranium isotope measurement protocols using Thermo-Fisher MC-ICP-MS (Neptune) at the Department of Geosciences, National Taiwan University.

The first protocol employs both Faraday cups and secondary electron multipliers (SEM), enabling simultaneous measurement of ^{234}U and ^{238}U despite their substantial abundance differences. By applying a retarding potential quadrupole lens to reduce ^{238}U tailing background for measuring ^{234}U ion beam on SEM, we achieve monthly 2-sigma variability of 1-2 permil for the $^{234}U/^{238}U$ determination. This reproducibility is comparable to within-run analytical errors. The second protocol measures ^{234}U and ^{238}U on Faraday cups, while monitoring the tailing background at half-masses at m/z = 233.54 and 235.54 on SEM. Despite potential deviations from true isotope ratios due to the interference of scattering ^{238}U ions, careful cup configuration design makes this method workable, with a monthly 2-sigma variability of ± 0.5 permil. Testing on international standards HU-1 and 112A by the two methods demonstrates good agreement with reported values. Comparing these new methods to previous approaches for measuring $^{234}U/^{238}U$, our design significantly reduces measurement duration from 30 minutes per sample to 10 minutes per sample with good precisions of ± 0.5-2 permil.

Advancements in column chemistry for isotope dilution U-Th dating on natural carbonate

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Abstract:
The purification of elements U and Th from matrix through column chemistry plays a critical role in carbonate ^{230}Th dating. The anion exchange resin AG® 1-X8 has widely been used for over half century; but its inefficiency in separating U from Ca poses a challenge, especially considering the substantial presence of Ca as the primary element constituting about 40% of carbonate. Inadequate separation of Ca from U fraction significantly suppresses ion beams of U isotopes by a factor of 5-10 on the mass spectrometer. Our experiments showed that the traditional method is suitable for carbonate samples below 0.5 g but faces challenges with larger sample sizes. Here, we propose an improved chemistry procedure with new UTEVA® resin for U-Th column chemistry for carbonate samples ranging from 0.01 to 3 g. Following sample dissolution, appropriate amounts of H2O2 and Fe2+ were added for efficient removement of organic materials and co-precipitation to effectively eliminate Ca. Subsequently, 0.2-g UTEVA® resin was utilized for purifying U and Th fractions from matrix by chromatography. This involves using 3 N HNO3 to remove Fe, Ca, Mg, and Sr, 4 N HCl to elute Th, and the 0.1 N HCl to elute U. Our findings indicate that this new procedure can successfully eliminate Ca and other major trace elements from both U and Th fractions. The high ionic selectivity of UTEVA® resin also ensures a recovery percentage exceeding 90% for both U and Th. This refined column chemistry presents a significant improvement in U-Th dating methodologies for carbonate samples of various sizes.

An earthquake slip simulator for gouges sheared at high slip velocity and high normal stress under pore-pressure-controlled conditions

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Rapid and large displacement fault slip leads to catastrophic events, including earthquake rupture propagation, tsunamis, and landslides. At shallow crustal depths, water-saturated (wet) clay-bearing gouges are a common component of fault zones. Therefore, shearing clay-bearing gouges with rapid and large displacement fault slip is of paramount importance for understanding earthquake physics and seismic hazard assessment.

Shearing wet gouges with rapid and large displacement fault slip, including high slip rates (1 m/s) and large displacements (meters), relied on the confinement of polytetrafluoroethene (Teflon) and were generally limited to low normal loading (< 2 MPa). In recent years, we have been engaged in the development of a gouge sample holder (as an earthquake slip simulator) to be equipped with the rotary shear apparatus installed at the National Central University. Thanks to the specially designed sample holder, wet gouges can be sheared at normal stresses up to 18 MPa in both drained and undrained conditions. Recently, the sample holder has been modified to allow pore pressure control. Our sample holder, which simulates a realistic earthquake slip in clayey gouges, has allowed us to understand how normal stresses and the presence of fluid affect the frictional behavior of clayey gouges and the associated mechanisms in different tectonic regimes, such as deep-seated landslide, fault zone, and subduction zone. In addition, based on the characterization of the experimental products, our sample holder helps in the recognition of slip zones recovered in drilling projects. With this new and improved experimental approach, we present an application of these data for studies of earthquake physics, but also friction-related processes of geological and civil engineering interest.

Keywords: rotary shear, gouge friction, pore pressure control, slip zone, friction-related process

The Design of a Low-Angle Active Leveling Device for Short-Period Ocean Bottom Seismometer

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Abstract

In this study, we focus on developing a low-angle active leveling device of geophone for Ocean Bottom Seismometers (OBS). The deployment of OBS in varied underwater environments poses a significant challenge due to unpredictable terrains, which often affect the positioning and orientation of these instruments. In such scenarios, the role of a leveling device becomes crucial, especially for self-floating OBS. Most of the leveling devices are designed with a 360° range, resulting in high costs and limited versality, our approach is informed by previous OBS positional data, suggesting that a limited corrective angle is adequate for underwater conditions. Our innovative leveling mechanism resembles a joystick in its transmission system, topped with a platform to enhance versatility. The control rod below the platform is controlled by two DC motors combined with worm gears, adjusting the rod along the X and Y axis with an approximate corrective angle of 30 degrees. For seismic sensing, our system utilizes one vertical and two horizontal geophones, housed in a custom sensor box to ensure the three axes are orthogonal to each other. This design simplifies the complexity of parts, combining off-the-shelf and custom components, offering a significant size and cost advantage. We have also tested its performance, with a focus on eliminating signal interference from resonance frequencies and assessing the system's stability. This includes a comparative analysis with older leveling mechanisms.

Keywords: ocean bottom seismometer (OBS), active leveling device, geoscience technology, geophone orientation correction, underwater instrument

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自製觀測儀器的優勢與挑戰

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IES 海底儀器實驗室自 2006 年引進 WHOI 研發的 BBOBS 起開始設立，一開始的目標只是為了因應 BBOBS 在台灣周邊海域收集海底地震資料所必須的佈放與回收工作，訓練基本海上作業的能力。但是由於我們對海下儀器的機械、機電特性經驗不足，可能疏忽了一些儀器維護上的細節，因此造成儀器無法收回的風險增加。一開始只有 50%的回收率帶來了很嚴重的打擊，才在 2009 年 IES 海底儀器實驗室結合國立中山大學海下所、國家實驗研究院台灣海洋科技研究中心組成 OBS 研發團隊 （OBE Team），開始自行研發海底地震儀。盤點十幾年來在 OBE Team 研發基礎上，已經完成 Yardbird OBS, Yardbird-BB, 海底電磁觀測儀 OBEM, 海底絕對壓力計 SAPG 的研發並且少量生產製作，所製作出的儀器設備除了支援 IES 郭本垣研究員的 ”台灣地區雙隱沒帶之地幔構造與流場”、” 西太平洋隱沒帶底部之非均向性與流場”、 國立台灣師範大學林佩瑩教授的 ”表面波陣列分析探討南台灣隱沒-碰撞過渡帶岩石圈剪力波速度構造”研究計畫，佈放在台灣東部海域和日本北沖繩海域，”探索地球系統: 太平洋遠征” 研究計畫，佈放在關島東方西北太平洋海域，也支援國立中央大學許樹坤教授之” 馬尼拉隱沒帶的海洋及鄰近陸上地球物理調查”研究計畫，在菲律賓馬尼拉海溝附近海域佈放收集海域地震資料。

水下儀器的組成，除了儀器本體之外，也需要有一些附屬設備，例如差動水壓計（DPG）、感震器平衡機構、和幫助儀器回收作業所需要的閃光燈標（Flush Beacon）…等。這些附屬設備雖然也可以由國外進口，但是價格高昂，經過本實驗室的研發，可以只用不到 4 成的價格就可以製作完成，省下不少的經費。甚至於可以把外購的流速儀懸掛在 BBOBS 上面而形成海底地震及流速儀，把自行組裝的 SAPG 儀器桶附掛在 BBOBS 上來同時量測海底地震和絕對水壓。這些彈性應用，是外購儀器所無法達成的。

本文將詳述各種自製儀器（包括 Yardbird OBS, OBEM, SAPG）在科學上的應用和工程上的優勢、研發構想、製作瓶頸、實驗過程、遇到的挑戰與解決的方法。:

關鍵字: 發海底地震儀 (OBS), 海底電磁觀測儀 (OBEM), 海底絕對壓力計(SAPG), 差動水壓計 (DPG）,

離散裂隙網路模擬及地下水流場建立
-以南投東埔地區為例

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摘　要

南投縣東埔地區的地質分區屬於雪山山脈板岩帶，岩層組成大多以變質砂岩及板岩的變質岩類為主，岩體原生孔隙率與滲透係數通常較一般沉積岩低，流體亦較不易以滲透方式於岩體中傳播，因此岩體之間的破裂面即成為地下水流體傳輸之主要路徑。早期研究大多著重於溫泉位置分布及鄰近地區地質環境調查，針對東埔地區地熱潛能區內的裂隙調查，亦僅止於裂隙走向分析及地質構造討論，較少探討裂隙延伸性及相關參數統計。因此為瞭解不同岩體裂隙群組之間的關係，進一步推估裂隙與地熱通道之關聯性，本篇研究工作擬進行岩體裂隙參數特徵化的量測工作，完成相關參數統計分析，提供後續地下水熱流模擬軟體進行運算。

本篇研究利用現地裂隙特徵調查搭配地質概念模式，建立地下水熱流數值模型，分析結果包括：(1) 裂隙位態經K-S檢定後均滿足費雪分布(Fisher distribution)，大致呈現西北-東南走向、東西走向及南北走向為主；(2) 藉由理論方法將視窗量測裂隙數據轉換為三維裂隙強度，約略介於0.005 m^{-1} ~ 0.1 m^{-1} 之間；(3) 分析地表裂隙軌跡長度及大尺度地表線型判識成果，裂隙尺寸的冪方律函數(Power-law function)指數為1.89；(4) 整合上述參數建立三維離散裂隙網路的空間分布，合理假設水文地質邊界條件及起始條件，進行地下水流場模擬，顯示東埔地區的熱液水流分布，受到水裡坑斷層及沙里仙溪斷層阻隔作用，上湧至河谷周圍地區形成地熱徵兆。

宜蘭平原溫泉井水溫的地熱潛能含意

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摘要

過去大多數的研究結果都認為宜蘭平原的形成跟外海的沖繩海槽張裂有關，張裂作用有可能引發深部的熱液流體向淺部移棲，使淺部蘊藏高溫的熱水。本研究收集近年來在宜蘭平原開發的深井溫泉井之井溫資料，井深約數百公尺到上千公尺，結果發現，各溫泉井同深度的水溫，宜蘭平原南側的溫泉井大都高於北側的溫泉井，若比較各井深度500公尺的水溫，宜蘭平原南側的溫泉井水溫大都約50~60℃，北側的溫泉井則只約30~40℃，以大尺度而言，地底下的熱流似乎有向宜蘭平原南側集中的趨勢。宜蘭平原過去的研究結果，在南側有一條東西向的高磁力異常帶，位置相近的羅東和五結附近，也有一條東西向的地震帶，土壤中的氣體濃度則顯示南側有一個較高的異常帶，綜整以上資料，本研究認為，宜蘭平原南側具有地熱探測潛能，值得在此區域規劃深層地熱探測。

關鍵詞：宜蘭平原、地熱潛能、溫泉井、水溫

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Calcium carbonate mediated CO_2 sequestration and methane formation in the deep subsurface biosphere: A study of decoding biomineralization process (二氧化碳封存衍生之碳酸鈣與甲烷生成：解碼微生物礦化作用與程序)

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Abstract.

The geological storage of carbon dioxide (CO_2) through calcium carbonate ($CaCO_3$) mineralization holds significant potential for mitigating the increasing concentration of CO2 in the atmosphere. This process is often expedited by indigenous microorganisms, which can biomineralize gaseous CO_2 into a stable solid form by modifying the physical and chemical conditions of deep subsurface aquifers. The injection of supercritical CO_2 can undergo various biochemical reactions within the host rock, transforming it into $CaCO_3$. However, the anoxic conditions of this system may lead to the production of methane (CH_4) as a byproduct during these biochemical processes. Herein, we focus on elucidating how microbial communities contribute to CH_4 production during the conversion of CO_2 into $CaCO_3$ through the biomineralization process in deep subsurface reservoirs. It's shown that sulfate reduction and methane oxidation are key mechanisms within the inherent microbial community, and have the potential to sequester CO_2 into solid $CaCO_3$ while concurrently producing CH_4 through metabolic activities under anaerobic conditions in a deep subsurface environment. Distinct bacterial species, such as *Desulfovibrio alkalitolerans* (DSM16529T), *Desulfovibrio cavernae* (H1M), *Desulfovibrio* sp. (H0407-12), *Methylocystis parvus* (OBBP), and *Methanosarcinales* (ANME-3), possess functional genes implicated in CO_2 sequestration through $CaCO_3$ precipitation under anoxic conditions and are capable of CH_4 biogenesis. Additionally, various biotic and abiotic factors in deep subsurface reservoirs, including pH, temperature, moisture, texture, extracellular polymerase substances, carbonic anhydrase, and urease enzyme activity, may influence CO_2 biomineralization-mediated

CH_4 biogenesis. These factors are directly correlated to enhancing CO_2 solubility in the aqueous medium of host rock, thereby influencing the rate of CH_4 biogenesis by accelerating $CaCO_3$ biomineralization facilitated by inherent bacteria.

Keywords (關鍵字): CO_2 storage (二氧化碳儲存), Carbon mineralization (碳礦化), CO_2 sequestration (二氧化碳封存), Methane (甲烷)

桃園濱海碳封存場址地下特性研究規劃

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摘　要

為達成2050淨零排放，台灣政府提出「十二項關鍵戰略」做為減碳途徑，期透過能源轉型、產業轉型、生活轉型、社會轉型等四大轉型策略達成淨零。台灣中油公司為執行政府政策，積極發展負碳技術中的碳捕捉與封存(Carbon Capture and Storage, CCS)，已初步規劃短、中、長期之碳封存場址建置計畫，短期為建置示範場址並作為對民眾溝通與環境教育之基地，中、長期則建置商業級碳封存場址，提供排放源碳捕捉後之最終處置。本公司依地質條件、排放源條件及土地等篩選因素進行評估後，認桃園濱海地區具備發展碳封存場址之潛能。

在場址篩選後，台灣中油公司利用過往油氣探採資料，對選定之場址進行初步地下特性分析，分析方法及項目除參考國外碳封存相關規範或指引(如：ISO 27914-2017、CNS27914:2017及DNV-RP-J203等)外，亦委託具國際碳封存作業經驗的公司提供場址開發經驗，確保未來碳封存作業之安全性。

為符合國際碳封存場址地下特性分析之要求，本公司將執行地質探井鑽探與震測資料採集工作。地質探井會透過連續取岩心及施作高階井測等方式，藉此了解地下岩層的各項特性，如：孔隙率、滲透率、相對滲透率、礦物組成、力學特性等；震測部分則陸續布設二維及三維測線，採集桃園濱海地區之反射震測數據，藉由高解析度之震測影像來更新既有層面與斷層解釋成果外，並以震測屬性連結井測及岩心試驗結果，以地下地質模型描繪出碳封存箱體(Storage complex)之範圍。另為了解二氧化碳灌注地下後對場址產生的變化，將以地質模型為基礎，執行水力動力學、地球化學、熱力學及岩石力學耦合數值模擬，評估不同二氧化碳封存機制及壓力隨時間之變化，藉此擬訂未來之灌注策略及監測計畫。

碳封存為淨零排放路徑中無法缺席之關鍵技術，在相關法規尚未完善前，台灣中油公司期望比照國際營運中場址的建置方式來推動內部碳封存計畫，並在過程中提供相關經驗予立法單位參考，促使台灣碳封存產業順利發展。

一種適合 CCS 場址的 3D 高解析震測法

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摘要

一般 2D 震測沿著道路施測，相對簡單，但 3D 震測需要將大量受波器擺成地面二維陣列，通常不太容易找到一大片安靜又廣闊的空間來佈設。陸地 CCS 場址常在工業區內，傳統 3D 施測方式，已經不可能。本研究提出一種 3D 施測方式: 環炸法，將受波器集中佈在鑽井旁，震源在外面遊蕩，如此可以解決大面積土地的問題。

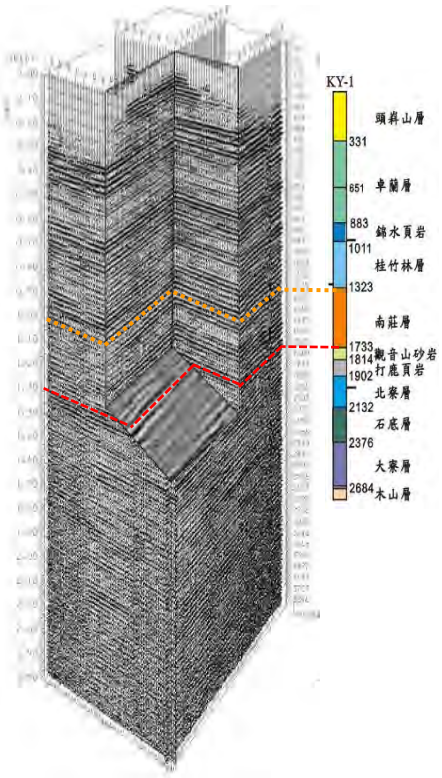
對 CCS 場址而言，只需將注意力集中在鑽井旁，監測 CO_2 儲存前後移棲情形，一般 1 百萬噸的 CO_2 會存在 1 km^2 的範圍，如此小的範圍需高解析震測才能解析。本研究測試的環炸法施測的範圍是: 1) 600 個受波器繞在井旁 200m x 200m，2) 震源在外面 2km x 2km 區域內盡可能找點施測，震源點數需達 800 點，3) bin(反射點)的大小在 10mx10m 以內，平均重合數在 40 以上。從工作量而言，3D 高解析震測經費不會低。

在 NEPII(國家能源計畫)年代，我們曾在桃園科學園區做過幾次鑽前 3D 測試，效果不差，可惜當時國科會未能認識到 CCS 的重要性，整個 CCS 計畫包括桃科鑽井都被迫中途取消，我們也就失去儲存後驗證的機會。本研究初步成果曾在 2013 年 AGU 年會報告過，受到 AGU 主辦單位重視，特別在 newsletter 中指出 CCS 震測的重要性。其實，環炸法更適合海上 3D 震測，將二維陣列佈在井旁的海床上，空氣槍在海面施測，但要有精確的定時及定位系統。

本報告展示桃科 3D 高解析震測實例，可以看到三維震測影像有趣且奇妙之處。

關鍵詞: CCS 場址調查、3D 高解析震測、桃園科學園區

桃科 3D



投稿議題：地球科學教育 EE

作者：徐毅振 Hsu, Yi-Chen

中文題目：初探台中市筏子溪之地質水文起源、進而開發結合考古遺址及近代平埔族群聚落分布跨領域內涵之走讀旅行

英文題目：Preliminary result of the origin of Fazi River and extended in-depth cultural tourism

投稿類型：口頭報告

摘要：
台中市筏子溪為台中盆地西側之主要水系，並成為近代台中盆地開發之始、重要灌溉水源，深受考古學界、水利單位及地方文史工作者重視。然而，現今對於筏子溪之起源論述，多認為筏子溪為古大甲溪匯入古烏溪之舊河道。而台中地區地質構造之前人研究多僅止於第四紀地質環境之探討，並未進一步論述筏子溪之起源。本研究透過實察地形特徵，並比對鄰近古大安溪河床、古烏溪河床及大甲溪新社河階群之特性，初步推論筏子溪之起源並非古大甲溪匯入古烏溪之舊河床，而是自大肚台地隆起後即為烏溪支流。
本研究進一步將筏仔溪起源議題結合考古遺址分布及近代平埔族群聚落分布，帶領對此議題有興趣的社會大眾實地走訪筏子溪沿線及相關水圳，進行文史及自然環境導覽，獲得社會大眾的參與及良好回響。本研究結合地質水文、考古遺址、地方文史之跨領域論述，以走讀旅行方式呈現，喚起社會大眾對人文發展及自然環境變遷的綜合認知及深度體驗感受。

中文關鍵字：筏子溪，台中盆地，考古遺址，地方文史，走讀旅行

英文關鍵字：Fazi River, Taichung Basin, Archaeological site, Local history and culture, In-depth cultural tourism

投稿議題：地球科學教育 EE

作者：徐毅振 Hsu, Yi-Chen

中文題目：結合考古遺址及近代人文歷史聚落分布重建台中海岸線變遷、進而開發具備跨領域科普推廣內涵之走讀旅行

英文題目：A reconstruction of coastline evolution of Taichung region and extended in-depth cultural tourism

投稿類型：口頭報告

摘要：
台中市牛罵頭遺址（約 4500 B.P.至 3400 B.P.）為台灣中部最具代表性之新石器時代中期考古遺址。然而，在此遺址出土之貝塚、網墜、矛鏃形器等漁撈生業文物，卻與該遺址現今自然環境明顯不符。前人研究已指出台灣近數千年之海岸線變遷與不同時期考古遺址分布密切關聯（陳文山，2014；劉益昌，2019）。本研究以前人研究為基礎，更進一步結合清水海岸平原近數百年來之平埔族群拍瀑拉社群聚落、漢民拓墾聚落之空間和時序分布，建立起近五千年來逐步向西拓展之台中海岸線、加上台中地區海洋沿岸流特性而重複形成內海潟湖─淤積消失之演化模型。
本研究進一步結合台中海線地區考古遺址時空分布及近代平埔族群文史，帶領對此議題有興趣的社會大眾實地走訪考古遺址及平埔族群聚落遺跡，進行文史及自然環境導覽，獲得社會大眾的參與及良好回響。本研究結合自然環境變遷、考古遺址、地方文史之跨領域論述，以走讀旅行方式呈現，喚起社會大眾對人文發展及自然環境變遷的綜合認知及深度體驗感受。

中文關鍵字：牛罵頭遺址，清水海岸平原，考古遺址，地方文史，走讀旅行

英文關鍵字：Niumatou Site, Chingshui Coastal Plain, Archaeological site, Local history and culture, In-depth cultural tourism

The irrigational advancement in Deccan India and associated Indian monsoon rainfall variations for the past three millennia

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ABSTRACT

Strategic planning in Deccan India led to the construction of water retention structures to preserve water and prevent erosion. Kings built tanks during the extended El Niño phase, coinciding with increased rainfall during the northeast monsoon. However, the relationship between these structures and the hydroclimate remains unclear. To decode the unknowns, we present a composite $\delta^{18}O$ record of two U-Th dated stalagmites from Kadapa cave in Deccan India that shows late Holocene monsoon rainfall variability and is compared to the development of ancient irrigation techniques, polities, and agrarian economies. Our monsoon record shows several prolonged droughts and floods associated with climate fluctuations. Moreover, the evidence from archaeology and inscriptions indicates that the former kingdoms carried out efficient mitigation strategies by constructing and maintaining water harvesting facilities. The oldest water storage structure in Deccan, India, which dates back to 800 BCE, was built during a monsoon drought at 2.8 ka. Mauryans founded India's first hydraulic civilisation, and Sātavāhanas utilized water wheels for irrigation to mitigate droughts. Pallava's and Chola's inscriptions and literature indicate the 'golden age of tanks' in Deccan India coincided with 937-1336 CE; that corresponds with the highly variable monsoonal rainfall, i.e., a major drought period due to the prolonged El Niño phase. Our stalagmite records show that during or after significant drought periods, the rulers constructed water-holding features, and three pulses of increased tank & pond constructions closely correlate to the monsoon droughts. The findings reveal the construction and maintenance of water-holding features during the late Holocene by the rulers and emphasize the importance of revitalising the traditional water-holding features for future sustainability.

論地質調查報告之著作權保護--從「地質法」第 17 條第 5 項出發

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地質法第 17 條第 5 項授權中央主管機關訂定「地質資料蒐集管理辦法」，其要求「政府機關或公營事業機構自行或委託辦理地質調查」、「接受政府補助或獎勵之機構、團體、學校或個人辦理地質調查」及「目的事業主管機關應於土地開發計畫審查通過或建照執照核發」後一個月內將報告中地質調查相關之書、圖、文件等，以紙本或電子檔提交中央主管機關。

前揭書、圖、文件部分由中央主管機關於官方網站公開其鑽孔坐標位置、數量、深度、鑽探公司、鑽孔地質柱狀圖與岩心照片，以上資料倘經由政府採購契約而來，因採購契約約定「廠商履約結果涉及智慧財產權者：廠商因履行契約所完成之著作，其著作財產權之全部於著作完成之同時讓與機關，廠商放棄行使著作人格權。…」而無著作權保護之爭議，即無「著作財產權」亦無「著作人格權」之疑義；若係經土地開發計畫審查通過或建造執照核發等情形，其地質鑽探報告之公開乃屬「依法令之行為」而無不法。

縱認網站所公開之鑽孔資料未盡符合地質法而不屬「依法令之行為」，其亦符合著作權法第 65 條「合理使用」要件，按最高法院 91 年度台上字第 837 號刑事判決：「惟著作權利用之態樣日趨複雜，舊法第 44 條至第 63 條規定之合理使用範圍已顯僵化，無足肆應實際上之需要，為擴大合理使用之範圍，新法（指 87 年 1 月 21 日修正公布）將本條修正為概括性之規定，即使未符合第 44 條至第 63 條之規定，但如其利用之程度與第 44 條至第 63 條規定之情形相類似或甚至更低，而以本條所定標準審酌亦屬合理者，則仍屬合理使用。」因此，地質鑽探報告自符合著作權法第 65 條「合理使用」而未侵害他人「著作財產權」，否則地質法公益之目的將不能達成。

至於「著作人格權」部分，仍須依照著作權法第 11 條至第 12 條與第 15 條至第 16 條依個別情形以觀，不能一概而論。此外，鑽孔地質柱狀圖係單純事實的描述，未涉及創作思想的表達，但若地質調查報告依此鑽孔地質柱狀圖而繪製「地質模型」時，該地質模型或有可能符合內政部台（81）內著字第 8184002 號解釋函之「圖形著作」而為著作權法所保護，併此敘明。

中文關鍵字：鑽孔地質柱狀圖、著作財產權、著作人格權、地質模型、圖形著作

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利用徑向基函數內插方法建立連續型海域地下層面模型之研究

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摘要

為擴大再生能源推廣,經濟部訂定2025年再生能源發電占比20%政策目標,預計2025年離岸風力裝置容量則達5.7GW以上。而離岸風力裝置的設置除了受到「保育與管制」相關規定,以及各類「經濟活動」等條件限制外,「基礎環境」更是影響離岸風力裝置設置的重要因素。因此調查並釐清海域地下地質資料更顯重要。地質調查需要高度專業與成本支持,海域地質調查更是如此,海域地質調查常以重點區域為主,因此造成資料分布範圍廣泛卻稀少,因此,如何有效的利用有限的海域調查資料建置廣域海域地下地層形貌,為本研究主要目標。

相較於陸地上地層狀態,海域地層相對變化較小、延續性較佳,因此,本研究考慮利用徑向基函數(Radial Basis Function,簡寫為RBF)內插方法建立海域地下層面模型。徑向基函數內插方法是一種廣泛應用於多維度資料內插的技術,在控制系統、機器學習、圖學處理等領域得到廣泛應用。其基本原理是將資料點視為徑向基函數的線性加權總和,因此無需事先考慮資料的結構關係,僅與資料點與函數原點的距離有關。這種方法雖然具有較高的時間複雜度,但在處理資料平滑化內插方面效果顯著,適用於無複雜構造之地下層面模型的建立。

本研究以海域地質調查成果「震測剖面」作為研究資料的基礎。通過解讀剖面資料,可以獲得特徵地下層面分布位置的關鍵資訊。將這些特徵層面位置標定後,將此視為已知層面資料點,利用徑向基函數內插方法,對這些資料點進行內插,從而建立特徵地下層面的連續型模型。此外,也可以通過這些模型,對地下層面的延展情況進行預測與分析,進一步瞭解層面在地下的分布形貌。

這項研究的結果對於海域地下結構的解析具有重要意義。通過建立連續型地下層面模型,可以更好地理解海域地質結構的複雜性,為海洋工程、海底資源開發等領域提供技術支持和參考依據。此外,基於徑向基函數內插方法的地下層面模型可確保通過已知控制點,能夠有效地補充和優化地下資料,對於海域地下層面模型的建立和應用具有重要的理論和實踐價值。

中文關鍵詞:離岸風電、層面、徑向基函數、海域地質、震測剖面

台語地質推廣經驗談

Experiences of geoscientific outreach in Taiwanese language

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2018年《國家語言發展法》頒布後，許多的科學領域都開始積極推動台語的推廣與教學，然而在地質領域的台語推廣活動仍相對欠缺。有鑑於經濟部地質調查及礦業管理中心在地質教育推廣工作已有深厚的成果，以及台灣台語路協會積極拓展兒童台語共學教育資源，因此媒合雙方於2023年8月於地礦中心地質多媒體展示場辦理了兩梯次的台語地質推廣活動。台語地質推廣的困難點，在於專有名詞的轉譯，在學術與通俗之間需要有一些斟酌。為了符合兒童為主的受眾，也結合唸歌的形式來增加趣味性。

從這次辦理台語地質推廣的經驗學習到，台語地質名詞的轉譯尚須討論與共識，可以從新聞與生活常用的名詞著手，討論合適的用字與發音。既有的文宣或網站內容也可以嘗試轉譯為台文書寫，讓台語推廣有更多的素材可以使用，也能培訓志工來合作進行推廣，以擴大地質科普在台語社群的能見度。

關鍵字：台語、地質推廣、科普教育、國家語言發展法

Keyword: Taiwanese language, geoscientific outreach, science popularization, Development of National Languages Act

池上斷層光纖地震觀測系統建置與初步資料分析結果

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摘要

分散式聲波感測儀 (Distributed Acoustic Sensor，簡稱 DAS) 或簡稱光纖地震儀可以使用光纖與解碼儀器建構高密度井下應變觀測。爲了建立池上斷層的高解析度近斷層帶的淺層地下構造，國科會 MAGIC 計畫透過池上斷層的地質鑽井，在井下設置光纖並沿著地表串接各井位，從保安宮後 (A1、A1-N 井) 向南經碾米廠 (B1、B2、B3、N1 井) 至萬安國小後 (D1、D2 井)，完成總長2500公尺的光纖設置工作，並在萬安國小設置光纖解碼器進行觀測。

本實驗執行於 2023 年底，目前已完成在保安宮後的 A1 與 A1-N 井區域的敲擊測試，測試選用兩種敲擊震源，除了傳統鐵鎚也使用中研院地球所自製的新式震源，並在地表以 2.5 公尺間距 (同光纖節點間距) 放置 18 台 SmartSolo 短周期地震儀，範圍涵蓋兩口井與地表 GPS 量測定樁位。經兩種震源各敲擊 10 次進行疊加，總共收集 6 個震源點的資料，其震源分布於地表基樁跟井位旁，結果可以獲取兩口測量井下的震波響應，並提供地表跟井位的絕對位置參考值供應光纖節點校正。

AI地震資料處理流程之建立：整合池上地震網與中研院寬頻地震網

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池上寬頻地震網是池上多維度觀測計畫(**M**ultidimensional **A**ctive fault of **G**eo-**I**nclusive observatory **C**hihshang, MAGIC)中為了監測池上地區的孕震構造所建立的微震監測網，目前共有 5 站。而為了獲得更完整的地震目錄，我們選取中研院寬頻地震測網(BATS)靠近台灣東部的 9 個地震站，進行地震資料整合與同時分析處理，以增加測站包覆度。本團隊從建站、資料傳輸，進而將資料整合至 AI 地震資料處理平台(SeisBlue)，完成 14 個地震站聯網，稱 ETBATS，進行近即時地震資料處理，我們可以在短時間內得到地震目錄，有效節省使用的人力與時間成本。在 2022 關山池上地震之後，本團隊開始持續接收即時網路傳輸的地震資料，並使用 SeisBlue 製作近即時地震目錄，發展推播系統，在更短的時間內得到地震的資訊。

關鍵字：池上多維度觀測計畫、地震觀測、AI 地震目錄、SeisBlue

池上微震觀測網近即時SeisBlue地震目錄：2023-2024年萬榮地震序列

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摘　要

池上微震觀測網為池上斷層多維度觀測計畫 (MAGIC，Multidimensional Active fault of Geo-Inclusive observatory Chihshang) 項目之一，結合池上及中研院地球所兩個寬頻地震網的即時波形資料，透過深度學習套件 SeisBlue 建立近即時微震目錄，監測池上斷層周圍地震活動，以期解析地震孕育與深度流體循環的關連。萬榮地震序列(震源位於中央山脈側光復至瑞穗間，經度 121.29 度，緯度 23.67 度，半徑 6 公里範圍內，震源深度 0-10 公里) 在 2022 池上地震發生後兩個月內，雖有被觸動但地震規模不大，而 2023-03-21 發生 M5.4 地震(深度 8.5 公里，暫定為主震)及 2024-01-28 發生 M5.3(6.6km) 及 M5.1(6.9 km)兩個中型地震後，該區域截至 2024-02-28，氣象署共發布顯著有感地震九個及小區域地震 28 個。本團隊透過池上近即時地震目錄，觀察到主震當日，地震數量從背景日地震數 50 個增加到五百個，第三天降至一半，第六天就降到一百以下，一個月內恢復到背景地震數量。而在 2024-01-28 當日，連續兩天日地震數量為 281 及 216 個，第三日就降至一百以下，第七天降至背景值 50 個，但 12 天以後的 2024-02-11~26 的 16 天內則類似群震行為，日地震數量從 100-230 個不等。建立近即時 SeisBlue 地震目錄可有效率的監測台灣東部南段的地震活動，快速提供孕震構造的斷層幾何與其活動特性。

關鍵字：池上微震觀測網、萬榮地震序列、深度學習、SeisBlue、近即時 AI 地震目錄、池上斷層多維度觀測計畫、MAGIC

Keywords: Chihshang micro-seismic monitoring network, Wanrong earthquake sequence, deep learning, SeisBlue, near real-time AI earthquake catalog, Multidimensional Active fault of Geo-Inclusive observatory Chihshang, MAGIC

The changes of pore pressure in the creeping fault zone triggered by the 2022 Chihshang earthquake sequence

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Abstract

MAGIC (Multidimensional Active fault of Geo-Inclusive observation Center) is located at the Chihshang creeping fault, situated at the boundary of tectonic plates in eastern Taiwan. This fault exhibits aseismic creep at a rate of 2 cm per year, alongside high seismic activity. Our goal is to comprehend fluid circulation within fault zones and its impact by monitoring hydrochemical and hydrophysical aspects across multiple dimensions. We also monitor nearby micro-seismicity and surface deformation. The Chihshang earthquake sequence of 2022 commenced with a magnitude 6.4 event on September 17 (local time), followed by a magnitude 6.8 earthquake the subsequent day. The epicenters were situated within the Central Range fault system, positioned to the west of our monitoring network. This provides a significant opportunity to observe co-seismic changes in pore pressure within the footwall and fault zone. The findings revealed that following the initial earthquake in the adjacent fault system, the pore pressure within the footwall rapidly decreased by nearly 100 cm within 15 hours. Concurrently, the pore pressure within the fault zone increased by approximately 25 cm during the same period. Subsequently, the footwall's pore pressure continued to decrease with the second earthquake and then slowly recovered. These alterations in pore pressure suggest that fractures underwent both opening and closure during stress migration.

台灣東部臨時地震觀測網

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地震分布是了解目標區域地下斷層幾何構造的第一手訊息，隨著地震資料不斷地累積，地下斷層幾何分佈與特性也將越清楚。2018 至 2024 年以來，台灣東部大規模地震每年不斷地發生，產生的餘震序列提供寶貴的斷層幾何分布與震源特性資料。而大地震發生後臨時密集地震網的佈設，更可詳實記錄餘震序列的時序與空間幾何。本團隊自 2018 年以來，在台灣東部佈設臨時密集地震網超過 10 次，監測儀器經歷 Texan、Zland 至 SmartSolo，從單分量到三分量，紀錄了台灣東部從北到南近 6 年來大地震餘震序列，也揭示著該區的三維孕震構造型態。此外，自 2021 年底以來，由國科會支持的池上斷層多維度觀測計畫 (MAGIC，Multidimensional Active fault of Geo-Inclusive observatory Chihshang)，開始架設池上寬頻地震網且並聯中研院部分寬頻地震站，完成池上微震監測網，並幸運地記錄到 2022 年關山池上地震從前震、主震到餘震的完整地震序列，釐清中央山脈斷層系統存在與否的長久爭論。同時，配合花東縱谷盆地的震測與三維震波層析成像結果，可以由淺至深探討中央山脈斷層系統與縱谷斷層系統間的幾何關係，藉以推斷菲律賓海板塊與歐亞板塊間，在台灣東部的劇烈變動過程。

Comparison of geochemical characteristics of soil gas and CO_2 emission between the Chihshang Fault and the Central Range Fault in eastern Taiwan

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Abstract

We first time compared the characteristics of gas emissions and sources between the Chihshang Fault (CSF) and the Central Range Fault (CRF) in the Longitudinal Valley of eastern Taiwan, selecting a period of relative stability with no significant earthquakes in the study region as the background period. Systematic measurements of CO_2 degassing were conducted with high spatial resolution, ranging from a few tens to hundreds of meters. Additionally, several soil gas samples were collected for gas composition and isotopic analysis. The results from the Graphical Statistical Approach (GSA) indicate that the CO_2 flux emissions from these two fault systems fall within similar ranges. The elevated CO_2 fluxes were found to be localized at specific sites, corresponding closely to the potential surface manifestation of the CSF and the CRF faults. It signifies the initial identification of surface CO_2 emissions associated with the CRF. The ^{13}C isotopic composition results from both faults indicate that the main sources of gas are a mixture of deep crustal and shallow biogenic origins. The findings suggest that the CSF and CRF systems can act as conduits connecting deep and surface gas reservoirs. Further repeated measurements or continuous monitoring of CO_2 flux is critical for improving understanding of the dynamic degassing processes related to fault activity and earthquake generation within the study area.

Key words: Chihshang Fault, Central Range Fault, CO_2 degassing, earthquake generation

影響卵礫石層介觀強度參數的微觀特性：現地直剪試驗離散元素法探討

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摘　要

卵礫石由於顆粒尺寸分布範圍極廣，造成取樣與室內試驗困難，工程特性參數僅能透過極少數現地試驗，甚至採用經驗法或類比法估計，因而出現極大的差異。卵礫石的粒徑分佈影響其強度參數，當粗顆粒含量超過20–35%時，粗顆粒含量及其幾何特性甚至主導了工程特性，摩擦角因粗顆粒的互鎖效應而增加，應變軟化程度也增加。儘管現地直剪試驗可以探求卵礫石層的力學特性參數，然而現地試驗因費用昂貴，試驗數量有限，往往無法考量影響卵礫石層力學特性的眾多因素，例如粒徑分佈、顆粒排列與堆疊方式，以致難於求得具代表性的特性參數。本研究採用離散元素顆粒流軟體，配合實驗設計法考慮不同水準的微觀參數組合，透過變異數分析求得影響卵礫石巨觀特性的微觀參數，以及其迴歸關係式；結合數量有限的現地直剪試驗結果，即可描述卵礫石地層力學特性參數的分佈範圍。本研究並以台灣桃園卵礫石層為例，說明所提方法的流程與應用性。

關鍵字：卵礫石、互鎖效應、現地直剪試驗，粒徑分佈

山腳斷層地下孔隙液壓變化誘發斷層重新活動可能性之模擬

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摘　要

本文章主要探討水力液裂工程造成地下孔隙壓力上升造成斷層不穩定，進一步誘發地震發生的可能性。我們選擇了台北盆地因為穩定性而備受討論的山腳斷層之參數進行模擬，利用蒙地卡羅法(Monte-Carlo Method)結合主軸應力等斷層參數進行大量的數據擬合。在計算出誘發斷層新活動的孔隙壓力上升區間後，我們就能夠定義不同孔隙壓力造成的斷層滑動潛勢(Fault slip potential, FSP)。同時，我們也利用斷層的走向、長度以及傾角等參數，建立高解析度的三維斷層網格模型，並在斷層附近處進行網格細化提升精確度。在高解析度的網格模型中加入不同位置的注水井並設定注水量，就能夠模擬出注水後的FSP分布。此模型未來能夠幫助我們利用模擬的方式挑選注水位置以及避免過量注入造成斷層滑動的頻率上升，對於像是地熱發電進行的尾水回注，或是油氣開發進行的水力液裂等工程的安全行評估提供良好的參考價值，同時節省許多探勘上成本以及降低工程上的風險。

關鍵字:水力液裂、蒙地卡羅法、主軸應力、斷層滑動潛勢、三維網格模型

Simulation of the possibility of fault reactivation induced by changes in underground pore pressure of the Shanchiao Fault

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Abstract

This research mainly discusses the possibility that hydraulic fracturing projects may cause fault instability due to the increase in underground pore pressure and induce earthquakes. We selected the parameters of the Shanchiao fault in the Taipei Basin, which has been frequently discussed due to its stability. For simulation, we used the Monte-Carlo Method combined with principal stress and other fault parameters to fit a large amount of data. After calculating the range of the increasing pore pressure that induces new fault activity, we can define the fault slip potential (FSP) caused by different pore pressures. Simultaneously, we also use parameters such as the direction, length, and dip angle of the fault to establish a high-resolution three-dimensional fault grid model, and refine the grid near the fault to improve accuracy. By adding water injection wells at different locations to the high-resolution grid model and setting the water injection volume, the FSP distribution after water injection can be simulated. In the future, this model can help us to select water injection locations and avoid to increase the frequency of fault slip caused by over injection, for the safe operation of projects such as tailwater reinjection for geothermal power generation or hydraulic fracturing for oil and gas development. The assessment provides a good reference value, while saving a lot of exploration costs and reducing engineering risks.

Keywords: hydraulic fracturing, Monte Carlo method, principal stress, fault slip potential, three-dimensional grid model

Uncertainty of Heterogeneous Hydrogeological Models in Groundwater Flow and Land Subsidence Simulations

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Abstract

Investigations of a hydrogeological model in a three-dimensional (3D) heterogeneous aquifer system are critical for groundwater flow and land subsidence assessment. The hydrogeological information for regions between boreholes embeds a large amount of uncertainty into the hydrogeological model, and thus affects numerical assessment. Quantifying the effects of the heterogeneous system and hydrogeological model uncertainty on groundwater flow and land subsidence simulations is thus important. Here, data from 46 geological boreholes in Huwei Town, Taiwan, were adopted to investigate hydrogeological model uncertainty. The one-dimensional continuous-lag Markov chain and the geostatistical method were used to analyze the spatial characteristics of hydrogeological materials and generate realizations of the hydrogeological model based on the assessment results. Estimated hydrological conditions and hydraulic parameters were applied to mitigate uncertainty not caused by the hydrogeological model. The mean of the land subsidence results in Monte Carlo simulations was more stable than the range of results for each individual case, where the mean value of land subsidence could be different. Therefore, the mean and variance results provide a reliable assessment with uncertainty information for land subsidence

simulations. The coefficient of variation (CV) was used to quantify the hydrogeological model uncertainty. The CV for land subsidence exceeded that of hydraulic head due to the non-uniform thickness of clay, despite the smooth flow pattern. The CV and variance distributions of the hydraulic head and land subsidence provide uncertainty information that can be used to guide site investigations. A heterogeneous hydrogeological model with uncertainty quantification should be carefully applied to land subsidence simulations to obtain reasonable results.

Keywords: Hydrogeological model uncertainty, Groundwater flow, Land subsidence, Markov chain model, Stochastic analysis, Choushui River Alluvial Fan.

精細測繪於順向坡調查應用-以台7線68k為例

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摘　要

先進測繪技術產製精細數值表面模型DSM，經後處理技術獲取高解析度模型正交投影影像，可輔助工程地質調查作業岩性分布識別及岩體工程特性評估。本文應用無人機攝影產製台7線68k處之順向坡路段精細三維露頭模型，在地層厚度達220m的高解析度模型正交投影影像中進行岩層厚度量測並指示弱層厚度及其位置。成果說明精細測繪於順向坡調查較傳統人力量測更具全面性，各層岩體產狀及其風化程度得以在高解析度影像中直接目視，並測繪其剖面及量化各層厚度。最後，數位實境地層柱狀圖視覺化直觀展示，將有助於邊坡防護與管理的精細設計與施工。

提升工程地質鑽探品質之初步探討

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摘　要

摘要內容在工程地質調查中，地質鑽探是瞭解地下地質資訊最直接之重要方式，可由鑽探所獲得之岩心辨釋，瞭解地下地質材料之組成與分佈、土岩性質及地下構造等訊息。同時，在地質鑽孔進行調查、試驗與觀測，可瞭解地下水位、地下水分層分布狀況及其水位變化，以及瞭解地中變位滑動面位置與滑動速率。而提取之岩心，可以在實驗室進行土壤與岩石試驗，瞭解地質材料之物理特性及力學特性，得到相關參數，據以建立工程地質模型。

工程地質模型建立基礎為劃分工程地質單元，地質鑽探即為獲取工程地質單元分類所需資料之重要方法。地質單元劃分合理性必須基於詳實之地質分層、岩心紀錄及柱狀圖建立，所以地質鑽探所提取之岩心品質，以及岩心辨釋成果，皆相當重要。

我國法規多有規定土地開發或工程建設前，必須辦理基地地質調查及地質鑽探，然業界常見為節省金錢與時間成本，工程地質調查及地質鑽探常僅作為SOP帶過，滿足契約要求即視為完成地質調查，缺乏對基地地質情形提出具體評估與建議，致長期屢有結構物或地基工程發生問題，且在追究之下，多為初期基地地質調查不實影響後續工程設計，進而引發安全性問題。而地質鑽探雖是專業工作，但各家廠商品質水準不一，無同業公會，亦無相關法規直接管理，多僅由業主方之督導人員監督鑽探品質。由長遠角度觀之，如在地質調查階段充分提升地質鑽探品質，可有效降低後續工程可能遭遇之風險，對於工程之金錢成本、時間以及安全性，皆有正面助益。

為求提升地質鑽探品質，以輔助地質調查成果之整體性，本研究在下列幾個面向提出相關建議，包括鑽探紀實與日報表管理、鑽探配合之工作管理(包括鑽探取樣、孔內試驗與監測等)、岩心辨釋、地質柱狀圖建立、地質鑽探報告品質管理等。

關鍵字：工程地質調查、地質鑽探、岩心辨釋、土地開發、工程建設

板岩帶與片岩帶地層交界的地質構造、邊坡穩定與岩體特性探討-以南橫公路霧鹿至利稻鄰近為例

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摘　要

本研究針對南橫公路霧鹿至利稻鄰近經常性崩塌路段，利用多時期遙測影像、沿線地表地質、不連續面調查與數位測繪建模，建構地質模型及進行岩體Q評分後綜合研析邊坡失穩的影響因素，最後探討板岩與片岩交界帶附近的邊坡穩定與岩體特性。

研究結果顯示，研究區域內2009至2015年的歷史山崩目錄顯示，板岩帶內的山崩數量大於片岩帶區域。而霧鹿橋以西出露的片岩帶與板岩帶地層交界以不整合接觸，邊界的岩性交界帶之Q值低於兩側圍岩，以RQD以及Jr差異較明顯。板岩帶內其岩性差異對岩體工程特性變化一般不及褶皺及斷層出露處顯著。片岩的葉理呈波浪狀且不連續面組的持續性不佳，葉理跟波長為公分等級的褶皺會連接組合成不同型態的破裂面。透過地表地質調查及數位測繪建模獲取相關量測資料，建構研究區域內的地質模型，以比對山崩發生區與地質構造的關係。中視尺度至巨視尺度的褶皺、斷層、層間剪裂、密集裂隙內的調適構造則造成岩體破碎，易成為岩屑崩滑、落石的發生源。

Trigger and Mechanism for the Late Ordovician Glaciation and Mass Extinction: *New insights from multi-isotopic constraints*

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The Late Ordovician (~485-444 Ma) recorded the first Phanerozoic glaciation peaking in the latest Ordovician and a major increase in biodiversity punctuated by the first of the "big five" Phanerozoic mass extinctions (known as Late Ordovician Mass Extinction, LOME, the second-largest mass extinction in Earth history), and was characterized by two discrete pulses, one at the beginning of the Hirnantian and the other about 1.0 Ma later, near the end of Hirnantian. The Hirnantian Stage records a pronounced positive $\delta^{13}C$ excursion (up to 7‰) observed globally in both carbonates and organics, reflecting global perturbation of carbon cycle in Late Ordovician oceans. To interpret the Hirnantian positive carbon-isotope excursion (HICE), two competing hypotheses have been proposed: [1] enhanced burial of organic carbon could have promoted a drawdown of atmospheric pCO_2 and ultimately led to the glaciation; and [2] enhanced weathering during low glacio-eustatic sea levels could have initiated HICE. In addition, widespread marine anoxia is commonly hypothesized as the trigger for the second extinction pulse.

Here we first developed an accurate and high-precision analytical protocol for both trace element ratios and the Li isotope analysis in marine carbonates, and then generated a high-resolution, globally integrated seawater Li isotope record (Copenhagen Canyon section, COK, central Nevada, USA) during the Hirnantian Age. A negative excursion of δ^7Li occurred at the warming period during Early HICE, coincident with increased carbonate Li/Ca and elevated $^{87}Sr/^{86}Sr$, strongly suggesting enhanced silicate weathering during the warm climate. By adding our new carbonate δ^7Li record, enhanced silicate weathering during high sea levels most likely have initiated HICE and caused LOME 1. Future investigations on high-resolution multi-isotope records (e.g. Mg isotopes) and numerical modeling will provide more information about the causes of the HICE and LOME 1.

中央山脈變質泥岩的地球化學觀察
--探討在漸進變質過程中流體和礦物組成對元素分布的影響
The influence of fluids and mineral compositions on elemental distribution during prograde metamorphism--A Geochemical observation of metapelite in Central Range, Taiwan

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過去在中央山脈西翼低度變質泥岩的研究中，顯示在漸進變質過程所伴隨的脫水/脫汽作用使岩石中的硼逐漸流失減少，親流體的硼/硼同位素的分布基本上遵守雷利蒸散模式，但也受到變質沉積岩中的礦物組成影響，本研究即嘗試進一步地探討在整個區域漸進變質作用下，中央山脈變質泥岩中，礦物組成以及流體作用如何影響硼同位素和其他微量元素的分布；本文初步呈現 XRD 礦物半定量分析、岩石全岩地化分析和萃取地化分析之硼以及其他微量元素化學分析的結果。研究對象包含丹大林道剖面、南橫剖面 >60 個變質泥岩樣本，XRD 半定量組成分析顯示大多樣本主要含石英(quartz)、白雲母類(Muscovite)、綠泥石類(chlorite)、鈉長石(albite)以及方解石(calcite)，前四者在大多數樣本都有被辨識出來，丹大林道只有在中央山脈側的少數樣本有辨識出方解石，南橫西翼樣本多含方解石但東翼樣本大多沒有，丹大剖面的雲母峰度顯示在雪山山脈部分變質度較低而在中央山脈的部分變質度較高，過去 Beyssac 溫度測定前者<400 °C，南橫雲母峰度顯示由西往東變質度變高，過去 Beyssac 溫度測定大約從西側~300°C 到東側~450°C，雲母峰度資訊與過去溫度測定相符；將萃取分析結果對比於全岩分析結果，顯示大多數樣本的元素萃取比例：鈣>90%、磷>70%、錳 10%~>80%， 以及鎂、鍶萃取比例也較高，相反地鋁、鉀、鈉的萃取比例僅 <5%，顯示萃取的可能來源礦物為碳酸鹽類、磷酸鹽類以及氧化物類，由於在大多數樣本中鈣的含量仍頗高，這可能意味著即使 XRD 未能辨識出許多樣本的方解石含量，碳酸鹽類仍少量地存在於這些變質泥岩中，可在漸進變質時隨壓力增加而溶解，提供變質流體中鈣的來源。南橫樣本的微量元素濃度分析結果顯示：磷、硼，和輕稀土元素濃度正相關，鈣則和硼、輕稀土和鈰呈負相關，硼也和 IA 族的微量元素 Li, Rb, Cs，以及 Be, Cr, Co, Zn, Ga, Tl 有正相關，可能意味著這些元素具有和硼元素相似的流體遷移行為。南橫剖面的硼濃度並沒有顯著的隨向東變質溫度變高明顯減少的趨勢，但硼與鈣含量呈反比，而單純以礦物組成混合的控因似乎無法完全地解釋硼濃度的變化量，較高的鈣濃度似乎和更多的硼的流失相關，或許這涉及脫水作用流體的遷移途徑和化學反應，例如 CO_2 的產生？但由於目前仍缺乏硼同位素分異的資料來作為辨識變質溫度以及流體來源的有力證據，以及鍶同位素解析全岩和萃取的鍶來源差異，待資料完整以後應可做更清楚的探討。

Performance of inorganic carbon with H_2 reduction of the EAAMS system at NTUAMS Lab

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Abstract

A graphitization system of H_2 reduction method connected to Elemental Analyzer (EA) for AMS ^{14}C dating was established in 2022 at the NTUAMS Lab. The CO_2 gas is generated by the complete and instantaneous oxidation of the sample via combustion with oxygen at a temperature of 1030℃, and then reduced by H_2 at 550℃ for graphitization. We denoted the graphite sample produced with the device as EAAMS. Over the past year, the total organic carbon (TOC) such as peat and plant were shown reliable results. We here present the AMS ^{14}C results of carbonate (inorganic) samples which were produced graphite by H_2 reduction method.

Fifty-four OXII international standards yield an average and standard deviation of 134.07±3.22 pMC (percentage Modern Carbon) that agree with the reported data. Our new system can produce good-quality graphite for inorganic samples containing about 1.0 mg carbon mass, and the pressure yield of graphitization is higher than 77.8%. The background test derived from the Devonian carbonate samples (NTUB) is as low as 0.24±0.06 pMC (n =11), corresponding to a ^{14}C age of 48 kyr BP. The working standard from a stalagmite in the Shaanxi Province of China has been adopted for system testing. The average of the measured ^{14}C ages is 6381±79 yr BP (n = 8) which is identical to the consensus value (6300 yr BP). The case study of stalagmites from South Ural Mountains of Russia showed the reliable ^{14}C ages (Chiu et al. submitted in this issue). Our graphitization system provides a more efficient and convenient way for organic and inorganic sample preparation for AMS ^{14}C dating.

Keywords: AMS ^{14}C dating, graphitization system, Hydrogen reduction, inorganic carbon

台灣西南部河川化學風化作用對於二氧化碳排放的控制機制及通量

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摘　要

化學風化為碳循環中的主要作用之一，岩層中的矽酸鹽及碳酸鹽與環境中的酸類反應，如碳酸、硫酸，將對二氧化碳的消耗與釋放產生不同影響。大氣中的二氧化碳經與水結合形成碳酸後，藉矽酸鹽風化反應而消耗；然而在造山地帶如台灣西南部麓山帶，高聳陡峭的地勢與持續的抬升運動，使地層不斷出露大量新鮮面，其中富含的硫化礦物，特別是黃鐵礦，氧化後與水結合產生硫酸，經風化碳酸鹽後，產生的陽離子與碳酸氫根在碳酸鈣補償時間(萬年)尺度以上，則會間接造成二氧化碳的淨釋放。相較於碳酸，硫酸對於地層中的碳酸鹽反應速率更快，風化作用更具優勢，然而硫酸風化的貢獻在現有的評估及二氧化碳通量計算方法中，不論是在空間及時間上皆需更多觀測資料來完備。由於岩石風化會對河水化學造成直接影響，故可透過河水溶解離子分析來反推風化反應的進行。本研究針對台灣西南部六條主要河川（八掌溪、急水溪、鹽水溪、後堀溪、二仁溪、高屏溪）橫跨乾、濕季數個時間點進行時間序列採樣，以評估不同季節、降雨、溫度等環境條件下，台灣西南部河川風化作用對於碳排的控制因素及影響。採集後樣本由ICP-OES測得主要離子濃度、以滴定法量測溶解無機碳（DIC），由化學式及河川流量資料進一步計算碳酸及硫酸造成的二氧化碳通量及風化速率。此外，亦透過量測硫同位素比值，評估自然源或人為源硫酸的貢獻比例。計算結果顯示台灣西南部的河水溶解物質中碳酸鹽約占近八成、矽酸鹽約占兩成；總體物質約有四成來自硫酸作用，且主要為碳酸鹽礦物的風化。濕季流量越大，硫同位素比值越趨近黃鐵礦端元，計算得出的硫酸風化比例亦相應提升約1.2 至 2.3倍，支持由硫化礦物產生硫酸進而造成風化的推論。在碳酸鈣補償時間尺度以上，台灣西南部風化作用在大量硫酸的參與下，二氧化碳排放通量估算介於1.16×10^{6}及2.11×10^{10} mol yr^{-1} 之間，各採樣點在乾濕季的通量差異可達數倍至數千倍。

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Palaeoenvironmental variations of the past 3000 years in Russian Altai: insights from ^{14}C and $^{210}Pb/^{137}Cs$ dating and elemental records of Lake Kolyvanskoe

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Abstract

The 20 AMS ^{14}C dates on a 96-cm long core (22-Al-02A) from Kolyvanskoe Lake in the Altai Krai, exhibit nuclear bomb ^{14}C influence in the upper 13 cm part. However, due to old carbon influence (OCI) introduced from human activity the bomb ^{14}Ccurve is not apparently. With selected ^{14}C dates (which have the least OCI), an age-depth model spanning the past 3000 years has been established by using Bacon model. However, the Bacon model cannot provide good age estimation with the nuclear bomb ^{14}C influenced age and often smoothed out rapid sedimentation changes. Therefore, $^{210}Pb/^{137}Cs$ dating results are used for chronology of the upper 15-cm part. A sedimentary hiatus seems to exist during the Little Ice Age (1850-1550CE) perhaps due to frozen surface of the lake. Elemental concentrations in 0.5N HCl leach fractions as well as organic C, N and C/N provide detailed climate and environmental changes in fifteen periods. I (1180~960 BC): low productivity and moderate surface runoff; II (960~700 BC): lower productivity and surface runoff indicating a sudden cooler period; III (700~420 BC): increased surface runoff and organic activity owing to high moisture content, higher water level; IV (420-40 BC): reduced surface input reflecting dry conditions; V (40 BC~190 CE): elevated detritus and organic productivity indicating wet and warm conditions; VI (190~350 CE): lower surface runoff and organic productivity possibly due to dry period; VII (350~420 CE): elevated surface runoff and organic productivity possibly because of sudden wet period; VIII (420~850 CE): declined detrital input and organic productivity, high salinity attributable to dry period; IX (850~1080 CE): the lake was fresh at moderately high level, low productivity and high surface runoff resulted from wet and warm conditions; X (1080~1120 CE): increase in lake salinity and reduced land input, reflecting warm/dry conditions; XI (1120~1200 CE): decrease in salinity and pH with increased lake level under wet/cooling conditions; XII (1200~1400 CE): increased salinity, pH and productivity due to warm/dry climates; XIII (1400~1580 CE): increased lake level with reduced salinity, pH and productivity under

wet/cooling conditions; XIV (1600~1950 CE): very low sedimentation rate indicated frozen condition with cold climates; XV (1950 CE ~ Present): the lake was saline, high organic productivity, stratified and anoxic environment with less territorial input, showing human impact.

Keywords: ^{14}C and $^{210}Pb/^{137}Cs$ dating; elemental concentrations; palaeoclimatic reconstruction; Russian Altai Lake Kolyvanskoe

臺東霧鹿地區地質探勘井鑽探成果

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經濟部地質調查及礦業管理中心依地質法執行全國地質調查，包含地質資源探勘之應用，並依法公開相關地質資訊調查結果，以滿足政府及國民對於土地地質環境認知的權利。由於花東變質岩區仍待釐清在變質環境下，地表高壓相岩塊的來源與形成機制，同時為擴充地下地質資源的利用，故規劃變質岩區地下地質資源整合調查研究，提供深層資源進階探查與利用之依據。

霧鹿地區之地質背景為一複背斜主控的構造型式，核心為霧鹿片岩，兩翼為利稻層，複背斜軸向北傾沒，霧鹿片岩夾有大崙變質花崗岩，在大崙溪之露頭為轆轤溫泉，過去研究報導地表可見湧泉，變質花崗岩峽谷明顯有蒸氣徵兆，但在新武呂溪，花崗岩體則可能隱伏於地下。在霧鹿複背斜兩翼，霧鹿片岩與利稻層之界限附近亦分別有溫泉露頭，如複背斜西翼之碧山溫泉與六口溫泉、東翼之彩霞溫泉，支持霧鹿地區蘊含潛在地熱資源。

本研究於 112-113 年度進行花東變質岩區深層地質鑽探，由工研院材化所團隊與土耳其 Ortadoğu 鑽探公司共同執行。在台東縣海端鄉霧鹿部落東西兩側各鑽鑿一口深井，規劃深度分別為 1,000 公尺與 2,000 公尺，用以探測地熱構造的相關特徵，並比對地表地質與地球物理探勘結果，提供地熱地質概念模式之重要控制資訊。霧鹿一 A 號井現已鑽至 1000.4 m 深，累計取心 934.5 m，淺層進入岩盤後為霧鹿片岩，在約 637 m 處鑽進至完整花崗岩體，直到完井深度仍未鑽穿，岩層交界與大地電磁地電阻剖面圖之低電阻位置呈現一致。鑽井完成停泵約 100 小時後，量測到在井下約 650~800 m 區段，井內最高溫度約 115°C；霧鹿二號井位於碧山溫泉附近，持續鑽進中。

Keywords: 霧鹿、探勘井、地熱地質模型、花崗岩

高能微波鑽探-玻璃強度與應力集中研究

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摘 要

鑽井過程中，應力集中的現象會隨著深度增加而增加。當應力集中現象超過岩石強度將造成岩石破裂，進而造成岩石崩落。為了避免岩石崩落，且安全到達預定之鑽探深度，鑽井時需搭配泥漿與套管。當鑽進至一定深度後，無法完全用泥漿維持井壁，就必須放下套管。美國 MIT 團隊近年研發「高能微波鑽探地熱深井工法」，提出以微波源熔融岩壁後，周圍冷卻後的玻璃化岩壁可取代套管，能節省鑽進時間、增加鑽井深度。然而，相關研究過往未曾評估玻璃物質的強度是否足以支撐現地應力。而本研究評估「高功率毫米波鑽探地熱深井工法」產生。為得知玻璃強度、推測玻璃襯管能承受的現地應力，本實驗使用中央大學岩石三軸(GCTS RTX-1000)進行單軸抗壓強度試驗，獲得單軸抗壓強度(UCS)，並以井壁崩塌的彈性力學解析解，進一步量化鑽井深度。我們玻璃圓柱頂部施以軸向應力，將樣品變形速率設為 5%/min，定速以軸向加壓直至樣品破裂，並測量軸向應變及側向應變。我們測量實驗前頂部有瑕疵或缺口的玻璃樣本，取得其平均破裂強度為 206 MPa，遠低於其他 6 組無瑕玻璃的平均值 437 MPa，顯示軸向應力會在缺口處產生應力集中現象。此外，強度最低的兩組樣本（327 MPa 和 56 MPa），其實驗過程的側向應變皆在試樣達到最大應力前，記錄破裂面的生成。我們以玻璃強度結合描述井壁應力集中的彈性力學解析解（Kirsch's Solution）、並在逆斷層應力場下使用猶他地熱田（Utah FORGE）的壓力梯度，計算出玻璃強度於不同深度能支撐的最大現地應力，分別為 3 km 的 140 MPa 、5 km 的 230 MPa 、以及 10 km 的 460 MPa 。根據目前現有的數據，雖無暇玻璃破裂強度皆可承受 5 km 以下的地層深度，但這僅供為玻璃強度的極大值，在真實鑽探過程中，玻璃的快速冷卻會有何影響，以及鑽井過程形成玻璃時帶有雜質或有缺口等問題，皆需商討。

高能微波鑽探-玻璃強度與應力集中研究

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非彈性應變回復法現地應力評估的統計分析與精進

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隨著科技文明的進步、經濟發展的提升，及為追求更高的生活品質，人們對於天然資源與能源開採、工程開發和廢棄物處置等各項需求也日與俱增。在這些發展的促使與推動下，地下開挖工程逐步普遍，也因此現地應力的量測及資訊趨於重要。現地應力的量測有諸多方法，如套鑽法、水力破裂和非彈性應變回復法等。其中以非彈性應變回復法(Anelastic Strain Recovery，ASR)為目前成本耗費較低與效率較高的現地應力測量方法(孫東生等人，2014)。ASR 法是以鑽井獲取地下深處岩心，藉由量測應力解壓後所產生的應變回復資料進以推算三維現地應力方向和規模的方法。

前人以非彈性應變回復法來進行應力場的規模回推，其解析方式是使用 18 個黏貼於岩芯的應變計測量 9 個方向的回復正應變規模，以最小平方法重建三維應變張量，進行三維主應變場的演算，轉換成主應力方向與規模。但得到的結果只有一組平均數值，且並未分析各主應變方向與規模的偏差量，以致無法說明數據的可信度，提供工程單位參考使用。本研究進行應變計配置與分析程式的改進，將原本 9 個方向應變數據改以 6 個獨立方向為一組單位，並於每個獨立方向使用 4 個應變計進行量測，再利用最小平方法與奇異值分解法重建應變張量，之後以共變異數進行機率與統計的計算，以數值的變數變化程度和期望值進行分析比較。

實驗樣本取於臺東南橫大崙溪，深度 140 米之片岩樣本。ASR 實驗黏貼 24 隻應變計，數據初步分析結果顯示為非典型安德森斷層應力場形式。最大、次大和最小主應變之位態分別為 141.14°/45.79°E、36.22°/14.05°E 和 293.74°/40.81°W，水平最大應力的擠壓方向為西北-東南向，主應力由大到小分別為 3.66、2.22 和 2.06 MPa。葉理傾向和傾角分別為 296.18°和 65.31°，葉理面的法向量與三軸主應變相距較遠，推測本樣本可能沒受到葉理面力學異相性的影響。

後續將得到的數據結果進行統計與總結，使 ASR 實驗應力精度的可信度增加。

關鍵字:非彈性應變回復法、現地應力
英文關鍵字: Anelastic Strain Recovery, in situ stress

廬山地區電阻率構造之初步研究

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摘　要

本研究採用37點大地電磁探測，研究分析廬山地熱潛能區(春陽至馬赫坡地區一帶)之地下電阻率構造。本區主要岩性為厚層板岩與厚層板岩偶夾薄層變質砂岩，局部為厚層變質砂岩偶夾薄層板岩。在破碎變質岩層裂隙內的高溫及熱水往往造成地層電阻率大幅降低，依據三維逆推後所獲得的三維電阻率模型進行分析，瞭解低電阻異常隨深度的分布可用於解釋潛在的地熱構造，以掌握潛在的地下地熱資源分布與傳輸途徑。其初步研究成果說明如下：

1. 高程-500 公尺以上低電阻區(<100 ohm-m)主要沿著濁水溪、塔羅灣溪及馬海濮溪分布在廬山及春陽二個區域，這二個低電阻區與高電阻區之邊界為向西傾斜。
2. 高程-500~-5000 公尺間約以濁水溪與塔羅灣溪交界處為分界，以西為低電阻區(<100 ohm-m)，以東為高電阻區(>300 ohm-m)，低電阻區與高電阻區之邊界則為向東傾斜。
3. 廬山區域下方之低電阻區與高程-1500~-5000 公尺間之低電阻區間呈現一向西傾之連接通道，意示其可能為一主要裂隙帶或為深部地熱源向地表傳遞之路徑。

臺灣南投縣東埔地區裂隙活化趨勢評估

Evaluation of Fracture Reactivation Potential in the Tungpu Area of Nantuo County, Taiwan

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摘　要

隨著淨零排放的願景不斷地被訴求與呈現，綠色能源的多樣性、自主性與永續發展更加被重視與強調。地熱能為綠色能源中重要的基載能源且有強烈的地域性，其探勘與開發需要彙整區域地質、地球化學以及地球物理等不同的資料，進行多尺度整合分析，以獲得較高之探勘成效，降低開發風險。臺灣受到歐亞板塊與菲律賓海板塊斜向聚合與隱沒反轉之交互作用，其火山作用與快速剝蝕掘升使得臺灣擁有為數不少之地熱好景區。位於火山地區之高潛能地熱區，多位於國家公園內，因法規之疑慮，未能積極地進行探勘，其他地熱區則多位於變質岩區。若要將地熱能列入臺灣重要綠色能源之一，有關變質岩區之地熱探勘與開發技術，需要投入大量人力與物力積極發展相關技術。

裂隙儲集層為變質岩區地熱能主要之開發目標，但裂隙易受到應力場之影響，可能成為導水通道或阻水構造，因此應力場評估與裂隙活化分析於變質岩地熱探勘極其重要。臺灣南投東埔地區位於西部麓山帶與雪山山脈交界帶附近，地殼範圍之震源機制解多數淺於10km，但位於西部麓山帶，少數震源機制解可達20km，且以逆斷層與走滑斷層震源機制解為主，而位於雪山山脈的震源機制解以走滑斷層與正斷層為主。應力反演結果顯示西部麓山帶區域以走滑斷層應力場為主，拉張軸為東北—西南向。雪山山脈區域以正斷層應力場為主，走滑斷層應力場為輔，兩應力場可能互換，拉張軸亦為東北—西南向。整個區域上，水平最大擠壓方向以西北方向為主。

利用高精度數值高程模型配合配合多向日照陰影圖、坡度圖與紅色立體圖，判釋地表線型約2923條。藉由三角網法評估線型位態，篩選後取得可信度較高的2820條地表線型，包含西部麓山帶1412條地表線型與雪山山脈1408條地表線型，大致以高傾角裂隙線型為主。

結合現地應力與裂隙位態資訊，計算各裂隙活化趨勢，分析資料顯示裂隙不安定性與擴張趨勢皆較高，但滑動趨勢較低。判釋之地表線型裂隙與地熱點相互比對的結果顯示，在東埔溫泉與樂樂谷溫泉附近有數條北北西與近東西走向的高角度裂隙交會，這些高角度裂隙有較高的不安定性與擴張趨勢，低滑動趨勢，顯示樂樂谷天然溫泉可能為熱液由這些裂隙交會處湧出地表而形成。進一步將比較高潛能導水裂隙位態之差異，以及野外查核，提供更完整裂隙活化趨勢資訊，以期促進臺灣變質岩區之地熱探勘與開發。

彰化斷層幾何形貌統計與分析

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摘　要

在執行機率式地震危害評估(PSHA)工作時，斷層傾角為用來描述斷層幾何形貌的參數之一，由於在有限的地質與地物調查結果下，斷層傾角的範圍常具有較高的不確定性。本研究利用資料統計及二維幾何模型疊加，同時探討斷層傾角機率分佈的不確定性(Probability distribution for Aleatoric unctertainty)與評估模型的不確定性(Model structure for Epistemic uncertainty)，以探討在評估斷層由淺至深的幾何位態時，前述兩者間的差異多寡及不確定性範圍為何。

此研究蒐集彰化斷層沿線之地質與地物調查之斷層傾角，建立斷層傾角資料庫，將其表格化與圖形化。斷層傾角經過常態分佈檢定後，確認10-50度之傾角資料分佈呈常態分佈，依數值統計方法可得出彰化斷層的傾角上界/中值/下界為17/30/43，權重分別為0.3/0.4/0.3 或 14/30/46度，權重分別為0.2/0.6/0.2。而二維幾何模型疊加的分析結果，彰化斷層的傾角上界/中值/下界為20/30/45度。

在對比統計結果與二維幾何模型疊加結果後，在中值的部分並無差異，僅在上與下界有2-3度的差異。由於此區域的構造空間分佈，使場址距最緩斷層面的最短距離皆小於10公里，使用統計結果於PSHA中並不會產生過大的差異(<0.1)，其優點在於可有依據的選擇信心區間的大小，結合二維幾何模型疊加之結果，可輔助評估團隊選取更近似的斷層傾角上下界與對應的權重。

關鍵字:PSHA、斷層傾角、常態分佈、彰化斷層、權重

Shallow geological structures on the Southern Segment of the Longitudinal Valley Fault

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Abstract

The Longitudinal Valley (LV) in Earthen Taiwan is a suture between the Philippine Sea Plate and the Eurasian Plate, and two major fault systems on the western and eastern sides of LV separate the Central Range and the Coast Range, respectively. On September 18, 2022, a Mw6.8 earthquake struck in the southern part of the Longitudinal Valley, which caused the surface displacements along the Yuli Fault and Chihshang Fault, which belong to the Central Range Fault System and Longitudinal Valley Fault system, respectively. However, the southern segment of Longitudinal Valley Fault system, the Lichi Fault, did not have clear displacements after this earthquake. Two questions are raised regarding the activity of the Lichi Fault: what is its geometry and extent? and should it be zoned Geologically Sensitive Area to mitigate risk through engineering design? In this study, we mapped the river-exposed outcrops, interpreted near-surface geophysical surveys (including electrical resistivity tomography and reflection seismic), and compiled existing and new shallow borehole data. As a result, the new borehole data at one site, the Lichi Fault likely slipped in the thousand-year range throughout the Holocene. The Lichi Fault is ‘active’ and warrants zoning or other forms of mitigation to minimize potential, seismically induced loss of life and property.

Keyword: shallow geological structures, Longitudinal Valley Fault, Lichi Fault, Holocene

臺灣地震帶 (1)

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本研究利用1990~2020年間的地震資料，應用震波層析成像法與地震分布，建立臺灣各地質構造區的地震帶（孕震構造）的三維構造模型，並分析臺灣與鄰近海域地震帶與大地構造的關係。由於地質構造特性與地震帶成因有極密切關係，因此依據陸海域的海岸山脈、脊樑山脈、雪山山脈、西部麓山帶、海岸平原、北部張裂帶、琉球隱沒帶與馬尼拉隱沒帶等地質構造區的特性，劃分了31個地震帶（包括2個火山地震帶）以及2個無震帶。

臺灣地震帶 (2)

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本研究劃分了31個地震帶（包括2個火山地震帶）以及2個無震帶，目的為了探討各地質構造區在不同深度的地震帶與地質構造的關係，這有助於了解地震帶的成因與活動特性。地震帶的建置主要利用多方面地震地質資料，包括震源機制、震波層析成像、地震分布、地震頻率以及第四紀地質構造等進行綜合分析。

地震帶計有海岸平原：北港高區無震帶。西部麓山帶：桃竹苗地震帶、中彰投地震帶、雲嘉南地震帶與高屏地震帶（第一級）；泰安地震帶、草屯地震帶、台中地震帶、阿里山地震帶、口社地震帶（第二級）。雪山山脈：李棟山、雪山與埔里地震帶。脊樑山脈：脊樑山脈地震帶（南段、中段、北段）、中央山脈斷層地震帶（和平段、鳳林段、玉里段、初鹿段、檳榔段）、東澳–南澳地震帶、玉山地震帶、寶來地震帶與阿禮地震帶。海岸山脈：縱谷斷層地震帶（嶺頂、瑞穗、池上、利吉－鹿野斷層地震帶）、豐濱地震帶、綠島–蘭嶼地震帶。北部張裂帶：濁水斷層地震帶、三星地震帶、沖繩海槽地震帶、龜山島火山地震帶、大屯火山地震帶。琉球隱沒帶：琉球隱沒地震帶、弧前地震帶、琉球增積岩體地震帶。馬尼拉隱沒帶：馬尼拉隱沒地震帶、馬尼拉增積岩體地震帶。

從增積岩體到台灣造山楔 --由南臺灣板岩分析切入

From accretionary prism to orogenic wedge: insight from the slate belt of southern Taiwan

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台灣島自恆春半島至台東的南端部分，處於馬尼拉海洋隱沒與弧陸碰撞之間的初始大陸隱沒狀態，是了解台灣造山帶起始與發育的關鍵地區。利用台東太麻里-金崙、至南田的海岸露頭，整合野外調查、顯微構造、與碳物質拉曼光譜地質溫度計資料，將變質與構造結合，對幼年期的台灣山脈演化進行約制。調查結果初步顯示，此處的南海沉積物廬山層未於海溝處被上覆板塊前緣刮起，而是俯衝至增積楔下方受向西伸向逆衝變形形成接近層面的初期板岩葉理，爾後於俯衝後期受向東伸向背衝變形疊加形成偃臥褶皺與二期板岩葉理；在俯衝末期，增積-造山楔受到菲律賓海板塊板內變形/呂宋島弧接近影響而受到橫移壓縮變形，使廬山層板岩再形成向北伸向的褶皺。於海岸的南北向剖面分析可見，二期板岩葉理與變質等度線皆受到向北伸向褶皺的變形，可知橫移壓縮變形於廬山層板岩尚未達變質峰值(~340°C)及俯衝最深處(約 11-12 公里)、向東伸向變形仍進行時就已加入。此結果顯示，北呂宋島弧與台灣山脈碰撞前的菲律賓海板塊內弧前壓縮，在中國大陸邊緣進入隱沒系統後很快就開始進行，並對隱沒帶上的增積-造山楔造成影響。

Orogenic wedge, Backbone Range Slate Belt, poly-phase deformation, raman spectroscopy of carbonaceous material
造山楔，脊樑山脈板岩帶，多相變形，碳物質拉曼光譜

Shear Velocity Structures beneath Southern Taiwan Revealed by Rayleigh Wave Tomography Using Amphibious SALUTE Array

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In order to obtain high-resolution seismic images beneath the transition from subduction to collision in southern Taiwan, we established a passive broadband amphibious seismic network called the Southern Array for the Lithosphere and Uplift of Taiwan Experiment (SALUTE), which has spanned southern and adjacent offshore southeastern Taiwan since 2021. Combining SALUTE data with existing stations from Broadband Array in Taiwan for Seismology (BATS), we extracted Rayleigh waves over a wide range of periods between 8 and 70 s, using cross-correlation functions of ambient noise between all the suitable station pairs, and from teleseismic earthquakes at 30 to 90 degrees away and aligned nearly on the same great circle path as the paired stations. All the inter-station path-average phase velocities measured as a function of period were then inverted for phase velocity maps and 2D shear wave velocity profiles.

Our tomography results reveal several key findings: (1) Across the eastern offshore to the west part of the SALUTE main line, a high-velocity anomaly potentially representing a subducted fore-arc fragment is found at depths of 70 – 100 km. (2) At depths of 10 – 40 km beneath the fore-arc region, a significant velocity contrast is observed to coincide with the seismicity. (3) A low-velocity anomaly located at depths exceeding 55 km beneath the subducted Eurasian slab in southwest Taiwan, is likely the source of the fluids for mud diapirs. (4) In the northwest of our study region near the Peikang basement high, a high-velocity anomaly within depths of 20 – 25 km is potentially associated with magmatic underplating. The SALUTE data expands observational coverage across southern Taiwan. By integrating both ambient noise and teleseismic data into analysis, our final Vs models offer greater insight into the crustal to lithospheric-mantle structures and dynamics associated with the transition from subduction to collision in southern Taiwan.

利用複數之自相關函數計算錢德勒擺動之品質因子

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摘　要

錢德勒擺動(Chandler wobble)為地球的極移(Polar motion)中受離心力變形的彈性地球轉動產生的週期運動，其週期值P與品質因子(Q-factor)為決定地球內部物理性質的兩項重要參數，兩數值大約為P=433.7±1.8日、Q約35至100 (Furuya & Chao, 1996)，其中品質因子由於固態地球與其他物質，如大氣間之角動量的轉換量隨時間的變化未知，因此存在相當大的不確定性。

本發表基於H.A.Cole (1968)，與以往使用解迴旋(Deconvolution)的方式不同，利用自相關(Autocorrelation)的分析直接自極移訊號計算品質因子。該文中已利用統計原理及蒙地卡羅法(Monte Carlo)實驗證實Random Decrement Technique (RDT) 對於一維實數的振幅可行，但錢德勒擺動可視為平面二維的週期運動，因此我們試圖將該方法擴張為複數平面上之二維擺動，並且驗證相同方式之可行性。透過模擬發現，若取樣的時間夠長，自相關函數與一維實數時一樣，會近似於受脈衝力矩所產生的極移運動，即錢德勒擺動之格林函數(Green's function)，並且能夠計算擺動週期，或取絕對值計算品質因子。

最後透過模擬探討各參數與資料處理方式是否有助於減少Q值的精確程度，並了解取樣頻率(Sampling rate)充足即可用以分析，徒增取樣頻率無助於品質因子的改善、Q值的偏差(Deviation)與取樣時間的長短有密切相關等，並由分析了解地球錢德勒擺動的週期不短且Q值大，因此目前約130年的極移資料長度不足，使用此手法估計之品質因子仍無法有效減少既有之誤差。

Using Hybrid Simulator to Integrate the Behavior of Carbon Dioxide in Sandstone Layers Under the Influence of Geomechanical Mechanics

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Abstract

To control the influence of global warming, researchers in worldwide have proposed various carbon reduction strategies. The Taiwan National Development Council (NDC) has also proposed twelve related strategies, among which carbon capture and storage is one of them. The goal is to reduce carbon emissions by up to 4.6 million metric tons by 2030, and to launch two carbon capture and storage (CCS) demonstration and verification projects by 2025. This study utilizes a coupled numerical simulator of geomechanics and fluid mechanics to investigate the injection and migration behavior of carbon dioxide in geological formations during carbon sequestration. This study employed the coupled simulation of Itasca's FLAC3D simulator and Lawrence Berkeley National Laboratory's (LBNL) TOUGH3 simulator.

This study uses data collected from IODP Expedition 337, a scientific well drilled in the open waters of Hokkaido, Japan. The simulation utilizes FLAC3D to simulate geomechanics and features such as geological structures, fracture distributions, etc. After obtaining physical parameters such as stress and deformation from the model, the data is organized and used to calculate the permeability and porosity of the geological formation. These values are then written into the TOUGH3 simulator for further simulation. After calculating the fluid fluctuations within the model, the pore pressure, capillary pressure, and thermal stresses are updated in the FLAC3D model to reflect the changes in force state. This completes one time step in the simulation process.

Through this coupled simulation, compared to using a single numerical modeling software, a more comprehensive and accurate assessment of the stability and safety of carbon dioxide sequestration can be achieved by considering both geomechanical and fluid mechanical aspects of CO2 migration behavior.

Keywords: Carbon sequestration, Coupled numerical simulation, safety assessment

Geology structural identification through 3D Resistivity Inversion of Magnetotelluric (MT) data in the Tatun Volcano Group (TVG), Northern Taiwan

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Abstract

Understanding subsurface electrical conductivity is paramount for characterizing geothermal settings, with Magnetotelluric (MT) methods serving as a cornerstone in geothermal exploration. This research focuses on the Tatun Volcano Group (TVG) in Northern Taiwan, employing advanced geologic structural identification through the 3D resistivity inversion of MT data. The comprehensive geophysical dataset, comprising 49 MT measurement stations, amalgamates information from both the ITRI (Industrial Technology Research Institute) and Computational Geophysical Research Group (National Central University) datasets. A meticulously developed 3D resistivity model, inclusive of resistivity cross-sections and maps at varying elevations, serves as a robust tool for identifying anomalies critical to conceptual models guiding future production field expansion. Noteworthy outcomes of this study include the delineation of three potential geothermal areas and their heat source within the 3D resistivity model. These areas are characterized by a distinctive geological profile, featuring a low-resistivity clay cap juxtaposed over a high-resistivity core. Of particular significance is the identification of the heat source as a hot dry igneous body with high resistivity, high density, and high susceptibility located 5 km beneath the southwestern region of the TVG. Emphasizing the geological significance of subsurface conductivity, this study advances the understanding of geothermal systems in the context of the Tatun Volcano Group.

Keywords: Tatun Volcano Group (TVG), geothermal exploration, Magnetotelluric (MT), 3D Resistivity

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重新解析西太平洋海底電磁儀資料並建構西太平洋上部地函電導率構造

洪振翔[1]、林佩瑩[1]、Kiyoshi Baba[2]、Hisashi Utada[2]
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摘 要

Characterizing the physical properties of the lithosphere-asthenosphere system beneath oceans, such as seismic velocity and electrical conductivity, is essential for revealing its enigmatic nature. We reanalyzed seafloor electromagnetic observations from 46 Ocean Bottom Electro-Magnetometers (OBEMs) across 27 sites in the Philippine Sea and the western Pacific Ocean, some of which offer up to 3 years of recovery data. This expanded on previous one-year data analyses by utilizing all available data and combining both standard and generalized remote reference techniques with land geomagnetic stations as reference sites. Our improvements to seafloor magnetotelluric (MT) responses yielded significantly reduced error bars and increased coherence between observed and predicted electric fields, especially at shorter periods. We performed subsequent conductivity inversions for each site, considering the 3D topographical heterogeneity overlaying 1D mantle model. Our results reveal similar lithosphere thicknesses (~60 km) beneath the sites located in West Philippine and Shikou-Parece Vela Basins, while the Pacific exhibits a thicker lithosphere, reaching about 210 km. We noticed significant lithosphere thickness variation within the Shikoku-Parece Vela Basin, consistent with earlier seismic study. We also introduced the use of induction vectors, an independent geophysical tool distinct from MT and not used in previous studies. After accounting for topographic effects in MT responses, we noticed an unexpected alignment between observed and modeled induction vectors, despite not explicitly fitting the vectors during the processes. Our combined approach, including 3D topography correction and MT response analysis, effectively reveals robust 1D conductivity models down to 300 km, while the induction vectors further provide insights into lateral electrical variations.

Re-visit Electrical Conductivity Structures in the Western Pacific using Seafloor Magnetotelluric Data

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Abstract

Characterizing the physical properties of the lithosphere-asthenosphere system beneath oceans, such as seismic velocity and electrical conductivity, is essential for revealing its enigmatic nature. We reanalyzed seafloor electromagnetic observations from 46 Ocean Bottom Electro-Magnetometers (OBEMs) across 27 sites in the Philippine Sea and the western Pacific Ocean, some of which offer up to 3 years of recovery data. This expanded on previous one-year data analyses by utilizing all available data and combining both standard and generalized remote reference techniques with land geomagnetic stations as reference sites. Our improvements to seafloor magnetotelluric (MT) responses yielded significantly reduced error bars and increased coherence between observed and predicted electric fields, especially at shorter periods. We performed subsequent conductivity inversions for each site, considering the 3D topographical heterogeneity overlaying 1D mantle model. Our results reveal similar lithosphere thicknesses (~60 km) beneath the sites located in West Philippine and Shikou-Parece Vela Basins, while the Pacific exhibits a thicker lithosphere, reaching about 210 km. We noticed significant lithosphere thickness variation within the Shikoku-Parece Vela Basin, consistent with earlier seismic study. We also introduced the use of induction vectors, an independent geophysical tool distinct from MT and not used in previous studies. After accounting for topographic effects in MT responses, we noticed an unexpected alignment between observed and modeled induction vectors, despite not explicitly fitting the vectors during the processes. Our combined approach, including 3D topography correction and MT response analysis, effectively reveals robust 1D conductivity models down to 300 km, while the induction vectors further provide insights into lateral electrical variations.

由地球物理資料窺探台灣東部變質岩區的地熱特徵

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國際間知名的地熱田大都是火山型的地熱構造，地熱探勘與電廠運維經驗相對豐富；而台灣地區因特殊的地體構造，造就了東部變質岩區的高溫廊道，但是變質岩區的地熱田在全世界並不多見，因此探勘經驗相對少，故其地熱構造特徵與火山型地熱田有何差異？是具有挑戰性且值得探討的課題。

本研究藉由經濟部地質調查與礦業管理中心在國內各場域推動的地熱地質探勘，收集了東部變質岩區幾個代表性地熱區的空中磁測、大地電磁及震波速度等地球物理資料，彙整後顯示三種資料具有相輔相乘的效果，因而架構出由淺到深的物性概念模型。初步顯示在高程約0 km至-5 km間有一局部向東傾的高速且低磁的基盤岩體存在，在此基盤之上的地層，由磁力及地電阻模型顯示為具有向東傾斜的推覆構造及向西傾斜的背衝構造，而在板塊推擠過程中造成的橫剪構造，有可能活化前述斷層構造或產生深切地殼的破裂帶，觸發深部熱水或天水經深循環加熱後向上湧到淺地層，而近期的張裂構造則可能形成淺地層的熱水儲集層，在大地電磁的三維地電阻模型呈現低電阻異常，這些構造將是在中央山脈東翼地質區進行地熱探勘時需關注的重點。

關鍵詞：臺灣東部變質岩區地熱構造、空中磁測、大地電磁、震波速度模型

使用震源機制和GNSS位移場進行工程尺度現地應力反衍

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摘 要

現地應力為地球資源探勘及地下工程設計的重要資訊，精細化現地應力調查成果兼具科學防災以及提高地質工程設計水平的效益。利用震源機制反衍現地應力為地球科學界常見探求區域尺度現地應力方向的途徑，配合設定的地層強度可以估計現地應力張量；而水力破裂、套鑽法等現地試驗量測所得現地應力常受到地層變異性、地質構造，甚至是試驗位置不連續面的影響，相較於區域尺度現地應力張量，不僅量值常有偏差，主應力方向也常不一致，以致工程尺度的現地應力評估，迄今仍是一大挑戰。

國際岩石力學學會建議一套最終岩石應力模型的評估流程，首先自世界應力圖中擷取相關應的評估結果，蒐集場址地形、地質，透過鑽孔及岩心等方法求得既有的現地應力資料，建立最佳估計應力模型；據以透過現地應力量測方法，如鑽孔進行水力破裂試驗或是取得岩心進行相關試驗，或是補充震源機制反衍結果，增補現地應力模型；再者將前述資料透過統計方法進行闡釋，或是建立數值模型考慮地形、地質與影響現地量測結果的因素，整合應力測定結果；最後反覆迭代調整，據以發展最終岩石應力模型。

本研究以車籠埔斷層鄰近區域為例，按國際岩石力學學會建議，利用有限差分法軟體建立數值模型，考慮地形、地質與構造的影響，並參考GNSS觀測所得速度給定邊界相對運動速率，透過正算分析反覆迭代，至地表變位速度逐漸接近GNSS觀測值。結果顯示現地應力主應力方向與地表位移且相關性，並受到地層分布與地質構造影響。本文方法可持續發展，據以評估車籠埔斷層鄰近區域最終岩石應力模型。

Sediment dynamics and coastal environments in the Holocene of southwestern Taiwan

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In 2009, Typhoon Morakot brought unprecedented rainfall to southern Taiwan, triggering a massive landslide in the mountainous terrain. Extensive research has been carried out on the landslide processes, in particular the catastrophic event at Hsiaolin village.

The staggering volume of sediment generated by Typhoon Morakot raises several questions: 1. Is this typhoon an outlier in terms of rainfall and sediment production? 2. Beyond the immediate sediment transport during the event, does sediment cascade from upstream to the coast? 3. Are these two questions related?

The coastal plain, which is vulnerable to sea level rise and land subsidence, has significant societal implications due to its high population density. While previous studies indicate a gradual seaward shift of our coastline over the past millennium, evidence linking sediment-generating events to coastal change remains scarce, partly due to limitations in the existing literature.

Our research efforts focus on upstream sediment dynamics, coastal environmental changes and their intricate interrelationships. By studying extreme events in the upper reaches of the Lao-Non River and establishing an age-controlled borehole near the mouth of the Kaoping River, we reveal a sedimentary evolution - from a pre-Holocene braided river to an estuarine environment and finally to a barrier island and lagoon around 7.5 thousand years ago.

Keywords: Taiwan, coastal environment, sediment dynamics, Holocene

Contrasting patterns of transient CO_2 cycle associated with chemical weathering in Taiwan mountain catchments

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Chemical weathering of minerals is a significant agent in transferring CO_2 between the atmosphere, hydrosphere, and lithosphere over geological time scales. Common mechanisms involve the dissolution of silicate or carbonate minerals by atmospherically derived carbonic acid or pyrite-derived sulfuric acid. To assess weathering-associated CO_2 fluxes, a simplified reaction model can be used, attributing riverine cations to either silicate or carbonate sources. This convention is applicable for most large river systems where silicate weathering dominates but can be problematic for small mountainous rivers when there is a significant deficit of charges from the sum of anions and calculated DIC. This charge imbalance arises from excess charge contributed by DIC produced from sulfuric acid, which can be corrected by incorporating CO_2 gas into the reaction framework.
Evaluating the brief duration of CO_2 production is challenging due to the greater number of variables compared to constraints. In this study, a computational algorithm was developed to analyze the complete range of CO_2 and DIC cycles associated with silicate and carbonate weathering. This method involved correcting cation concentrations for non-weathering sources and partitioning them into the contributions of modeled silicate and carbonate minerals using the Monte Carlo algorithm. The computed cations for silicate and carbonate were then transformed into charge equivalents and balanced with the anion charges contributed by sulfate and DIC, with additional stoichiometric constraints for CO_2 and DIC-related sulfate. The computational scheme was then applied to calculate the weathering-associated CO_2 fluxes for the Pei-Nan and Kao-Pin catchments. Potential controlling mechanisms, such as lithology and landscape, will be addressed and presented.

Keyword: CO_2 cycle, Taiwan mountain catchment, chemical weathering

上次冰盛期以來南部海岸之高頻率沈積層序

High-frequency depositional sequences in the south coast from the Last Glacial Maximum

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摘　要

影響台灣西南部前陸盆地堆積的因子除了全球海水面升降之外，還有快速的構造沈降、大量的沈積物供應、差異的沈積源岩、乾濕分明的氣候等。為了探索這些因子造成的高頻率沈積層序，以解析對應的海岸環境變遷，本團隊利用高屏溪與曾文溪海岸新鑽取的9孔150–250公尺深岩芯，進行沉積相與層序分析。

各井岩相特徵顯示的沈積體系相近，都屬於洪泛平原－洲瀉－三角洲架構之下，最大差別是高屏溪岩芯有來自辮狀河沖積平原的變質砂岩與板岩礫砂層，曾文溪岩芯則有來自曲流河氾濫平原的顆粒度向上變細序列砂泥層。在台江內海、倒風內海與大鵬灣鄰近孔位中，岩芯常有堆積於瀉湖的厚泥層夾砂層，海相貝類與植物碎屑化石豐富；伴隨出現的岩芯常是堆積於沿岸沙洲的貝屑質厚砂層，層理與紋理發達、淘選良好。高屏溪與曾文溪河口鄰近孔位中，岩芯常有向上顆粒度變粗與砂泥比例增加的序列，伴隨著層理與層厚漸增、海相化石含量則漸減，反映三角洲矽質碎屑沈積物向外海加積的過程，漸次取代以海相生物遺骸與遺跡為主的陸棚堆積層。

層序界限是沈積相向上變深的界面，並且具有堆積緩慢或間斷的特徵，包括古土壤層與強烈生物擾動的貝殼碎屑富集層。界限之間的沈積層序則呈現沈積相向上變淺，洪泛平原的層序反映河道遷移、廢棄到充填的過程，洲瀉與三角洲體系的層序則指示相對海水面變深/海岸線內移再逐漸變淺/外移的過程。

在地表以下的第14個層序界限，各井深度在140–210公尺之間，普遍有一層數公尺厚的古土壤，其下的岩芯已是上次冰盛期以前的產物（老於25千年前），其上岩芯年代則不大於19千年前。由此推算，本區域冰盛期後的層序代表平均約1.4千年週期的沈積循環，冰盛期的沈積間斷缺失約4－5個沈積層序。

關鍵詞：高屏溪、曾文溪、上次冰盛期、高頻率沈積層序、相對海水面變化、1.4千年週期

Key words: Kaopinghsi River, Tsengwenhsi River, Last Galcial Maximum, High-frequency depositional sequence, relative sea-level change, 1.4 kyr

台南學甲宅港3.8萬年來沉積物內孢粉化石紀錄

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摘　要

宅港位於台南市學甲區東北方，本研究分析鑽取於宅港國小長達152米岩心所保存的孢粉化石，以重建台灣西南部之古環境變遷。基於19個放射性碳十四定年結果所建立的年代深度模式顯示，該沉積層約包含3.8萬年以來的紀錄。其在15.5-4.8 ka呈現較高的沉積速率，反映晚更新世以來全球海平面上升造成沉積速率增加的結果。孢粉分析結果顯示，沉積物內主要的木本花粉以鐵杉屬、松屬、桑屬、赤楊屬、櫟屬、栲屬、杜英屬為優勢。草本花粉則有艾屬、蕁麻科、禾本科、莎草科與香蒲屬。蕨類孢子則有單溝孢子、三溝孢子、卷柏屬。農耕禾本科花粉的存在則顯示晚全新世以來持續有人類在該區域進行農耕活動。基於上述孢粉所重建的古環境變遷資料，再與屏東大鵬灣2萬年來孢粉資料進行對比，以提供上次冰盛期以來台灣西南部古海岸變遷與人類活動的相關資訊。

玉山山脈兩翼荖濃溪與旗山溪的上游沖積扇階地發育

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摘　要

玉山山脈兩側的荖濃溪與旗山溪流域是高屏溪主要的集水區，在分水嶺兩翼的上游主支流匯口處，皆可觀察到許多由厚達50-250公尺、混雜河流與土石流礫石層，且由支流下切發育的沖積扇階地。目前已知，這些階地是支流集水區發生大規模崩塌之後所發育，部分支流至今仍持續向下搬運的大量堆積物，甚至覆蓋了原有的階地面，或加積了原以下切為主的主流河道，顯示這些階地的發育年代與加積規模並無規律。

基於現有的大量14C年代資料，荖濃溪右岸階地的發育年代可大致分為12.5-11 ka、6.5-5.3 ka、 3.5-2.7 ka和1.8-1.1 ka階段，其中又以1.8-1.1 ka的加積事件保存規模最大，並且特定事件似乎只發生在個別支流，如莫拉克風災等事件顯著對布唐布納斯溪造成大規模影響。相較之下，旗山溪左岸階地的發育年代集中在7.9–7 ka和1.8–1.1 ka，以7.9–7 ka的加積事件保存規模最大，並且分布在數個支流，雖然1.8–1.1 ka的加積事件也同樣發生在荖濃溪，但規模差異甚大。儘管玉山山脈兩側的荖濃溪右岸與旗山溪左岸有著相似的構造和氣候背景，但這些階地發育的不等時與不等量現象，說明了個別支流對於極端氣候事件有著不同的反應，這導致支流的沉積物供應與發生頻率存在差異，進一步對主流河道與下游高屏溪平原產生不同程度的地形演育影響。因此，後續我們將進一步從個別支流的地形特徵，討論其階地發育差異，並試圖與高屏溪平原發育建立關係。

以無人機載光達與多期數值地形模型討論快速變化的河道上沉積物遷移行為：以荖濃溪寶來至六龜河道為例

The redistribution behavior of river sediments along the rapid-changed riverbed revealed by the UAV-borne LiDAR and multi-period DEM analysis: a case study from Baolai to Liouguei, Laonong River, southern Taiwan

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摘　要

氣候變遷下極端事件是近期科學研究與政府尋找調適措施的熱門議題，極端事件的強降雨造成洪水與山崩，對荖濃溪縱谷中河階與沖積扇上村落居民的生命與財產造成嚴重的威脅。荖濃溪河道是快速變化的：長期而言，前人研究根據河階與定年資料，歷史上的極端事件曾造成較今日高出最高百公尺高的河道沉積物；短期而言，工程報告指出主要道路時常受到極端降雨事件而阻斷。面對變遷快速的河道，需要高時間與空間解析度的定量方法，才能一探河道沉積物物的輸入與重新分配。無人機光達提供較空載光達更低成本、彈性作業方式與高空間解析度的河道地形測繪成果，為此議題提供適合的材料。本研究使用政府開放資料以及近期無人機載光達共五期的地形模型，開放的地形資料提供大範圍、長時間、較低空間解析度的模型，可以討論長時間河道變化概況與沉積物的來源；以無人機載光達測繪的地形有較高的空間解析度，針對沉積物的空間分布有更細緻的描述。針對前述地形模型，以DoD（DEMs of Difference）的方法處理出四期的地形差異數據，以多組的河道剖面與DoD剖面進行分析，討論在極端事件後在寶來至六龜河道大量輸入的河道沉積物，在短期時間尺度下，如何被重新分配至下遊河道與搬運距離等訊息。分析2003、2011、2016年的地形資料計算出兩期DoD數值結果顯示，第一期結果觀察到在寶來與新開附近各有4至5公里長的沉積物輸入至主河道，河道堆積高度約8至10公尺，而第二期的結果顯示寶來附近的沉積物被搬運約3.5公里至荖濃一帶，堆積可達5公尺，而新開附近沉積物則平均下切約2至3公尺。依據現有資料，第一期河道變化主要由莫拉克風災後所產生，第二期河道邊化可能由2012年610豪雨與隨後重要事件貢獻。研究成果提示河道的變遷主要由極端氣候下強降雨事件所影響，期本研究方法與成果能提供快速變遷的河道上提供定量的描述，提供地質科學與工程方面的進一步研究的方向。

Spatiotemporal variations of organic carbon source and microbial degradation in the Gaoping River basin

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Rivers, as pathways for weathering products to the ocean, are vital in global carbon cycling. This study investigates the significant yet understudied role of small mountainous rivers (SMRs) in global carbon cycling, focusing on Taiwan's Gaoping River. It examines how microbial community composition and metabolic potential within these rivers respond to extreme weathering events that cause fluctuating water levels, such as rainstorms and landslides, and the resultant impact on carbon transformation processes.

Notable spatial variations in microbial communities were observed from the Gaoping River headwaters to its estuary, influenced by water level fluctuations. Lower water levels promoted higher microbial diversity, suggesting selective environmental pressures, while high water levels enabled species persistence, indicating a mass effect on community assembly. DNA and cDNA analyses revealed distinct microbial community clustering by water level.

Utilizing Biolog EcoPlatesTM for metabolic profiling, upstream sites showed greater capacity for decomposing various organic carbon (OC) susbtrates, particularly for polymers during high water levels, which diminished towards the estuary. However, during low water levels, the estuary conversely exhibited the highest substrate richness, with potential utilization of all 25 OC substrates tested. These findings highlight the influence of shifting water levels on spatial and temporal variance in OC degradation capacity.

In summary, this study of the Gaoping River underscores the significant role of SMRs in carbon cycling dynamics within riverine ecosystems. It provides new insights into microbial OC utilization as mediated by interactions between spatial location within the watershed and temporal fluctuations in discharge and water levels.

臺南玉井盆地口宵里斷層的斷距分析

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摘要

口宵里斷層位於臺南玉井向斜西翼，斷層呈東北走向，一般認為是烏山頭斷層的背衝斷層，在曾文溪畔劉陳灣一帶出露最為完整。由於玉井向斜朝南傾沒，本研究可比較位於向斜軸部（斗六剖面）以及向斜西翼（東曾文溪剖面）出露的沉積層序與生物地層，獲取斷層斷距資訊。

斗六剖面呈南-北向，底部由巨厚的海相砂泥層組成，其上被兩套海底水道相砂層與海進砂泥層所覆蓋。東曾文溪剖面呈西北走向，在劉陳灣一帶被斷層截切，斷層上盤為巨厚的海相泥層及生物擾動砂層佔據，下盤出露塊狀砂層及其上覆的海進砂泥岩。鈣質超微化石分析結果，顯示此二剖面具馬丁尼氏所稱 NN18 與 NN19 生物帶。綜整沉積層序與生物地層資料，研判東曾文溪剖面斷層上盤與下盤可分別以 NN19 生物帶底界及海進砂岩與斗六剖面相比對，評估斷距約 350 公尺。

臺南曾文溪剖面走馬瀨至玉井一帶中–更新統微體化石生物地層

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摘　要

臺南麓山帶位處3個不同地層系統的交界，由於此區岩性變化快速，不同地層系統間的對比面臨相當的挑戰。為此，我們針對曾文溪剖面烏山頭斷層上盤出露地層，建立鈣質超微化石及浮游性有孔蟲生物地層，依序辨識出指準化石*Discoaster berggrenii*、*Reticulofenestra pseudoumbilicus*、*Discoaster pentaradiatus* 絕滅面，以及*Gephyrocapsa oceanica*始現面，配合其他輔助化石可分區分出馬丁尼氏所稱NN11、NN12-15、NN16-17、NN18以及NN19等鈣質超微化石生物帶。在浮游性有孔蟲分析上，可見指準化石*Globorotalia plesiotumida*、*Globorotalia tumida*、*Sphaeroidinellopsis kochi*、*Sphaeroidinella dehiscens*、*Dentoglobigerina altispira*、*Globorotalia crassafomis*、*Globorotalia tosaensis*及*Globorotalia truncatulinoides*，相當於卜勞氏所示N17至N22等浮游性有孔蟲生物帶。這2種不同的微體化石生物帶可相互驗證與比對，指示地層的年代相當於中新世晚期至更新世早期，提供更具可信度的生物地層資料。前述成果可與烏山頭斷層下盤出露地層相比對，並可組合代表早期臺南盆地北側的沉積層序與生物地層。

早更新世二仁溪東剖面古亭坑層浮游有孔蟲群落變化及其古海洋學意義

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摘要

本研究嘗試透過高雄市田寮區一帶分佈之古亭坑層泥岩中採集之浮游有孔蟲化石進行動物群落分析，在所謂的“二仁溪東剖面“中共計 110 個樣本根據前人研究中有 82 個落在早更新世(2-1.2 Ma)之間。本研究共計辨識了 27 個種屬之浮游性有孔蟲。

將樣本中具有超過 200 隻可辨識的浮游性有孔蟲計數並且計算相對豐度，發現共有有五個主要熱帶種屬在整段早更新世的研究段落中平均超過 5%以上，種屬分別是常見的熱帶表層水種：*Globigerinoides. ruber* 與 *Trilobatus sacculifer* 以及次表層水種: *Pulleniatina obliquiloculata* 與 *Neogloboquadrina dutertrei* 和熱帶區域中常見的湧升流種屬: *Globigerina bulloides*。

本研究將表層水與次表層水種數相加討論，發現表層水種數在整段研究段落中範圍大約為 30-70%，顯示二仁溪東剖面一帶的古亭坑層泥岩在早更新世主要皆落在較為溫暖的熱帶海洋狀態，但是次表層種屬相對含量大約落在 10-30%之間，與南海與沖繩海槽一帶第四紀紀錄範圍接近，但是特別在前人磁生物地層學控制之年代大約 2-1.6 Ma)之間，次表層種屬的相對含量大多超過 20%。本研究初步推測此微體化石群落變化有可能紀錄了熱帶太平洋暖池形成事件的變化。

此外湧升流種屬在早更新世的研究段落中，相對豐度可以有 5-25%之間的變化，顯示此區域的生物生產力隨著時間有顯著變化，目前現代台灣近岸尚無相關現代觀測，但在早更新世時台灣西南沉積盆地是否具有湧升流系統或是高生產力區域，以及這樣的系統受到何種環境因素控制，亦是未來可繼續深入發展的研究方向。

二仁溪東剖面古亭坑層所發現之變形有孔蟲分布及其可能應用初探

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摘要

台灣西南一帶廣復之泥岩地帶不僅在風化侵蝕後的地形面上造就了有名的惡地地形，在另外一個方面，塊狀缺乏可供辨識層面的泥岩也造成跨區域的地層對比及此區域的構造變化研究上造成長久以來的困難。

本研究再訪前人研究所謂“二仁溪東剖面”的古亭坑層泥岩段落，自高雄田寮古亭橋至鹿埔向斜地區，再訪與新發現共計 42 個剖面與採集 110 個泥岩樣本。

在處理並嘗試辨識有孔蟲微體化石時，本研究發現在小滾水斷層/背斜西側有 19 個泥岩樣本中，具有明顯“變形”至幾乎無法辨識的有孔蟲化石。且這些變形之有孔蟲殼體大多完整，房室上皆可觀察到殼體孔洞等等結構，但是單個或是多個房室與整體殼體的形態扭曲變形導致在光學顯微鏡下辨識相當困難。故此本研究暫時排除這些變形之有孔蟲是再搬運過(reworked)的化石。而如果計算變形有孔蟲與總有孔蟲的數量，可以發現在這些區域中有數個段落變形有孔蟲佔總有孔蟲數量甚至可達 300 隻/g (總粗顆粒重量)。

根據前人磁生物地層顯示，自上新世至早更新世之間具有數個明顯不連續(disconformity)的邊界影響，而這些區域恰巧就是整段二仁溪東剖面區域中，唯一有出現變形有孔蟲殼體的區域，這樣的相關性是否顯示此區域受過後期構造作用導致生物地層不連續以及微體化石變形？這是目前本研究初步提出的開放性假設/問題。

這些變形有孔蟲仍須經過更進一步的結構與細部檢驗，甚至是地球化學的分析，但此種變形微體化石是否可以進一步作為台灣泥岩分佈區域潛在的構造應力分析工具，值得後續研究更進一步探討。

二仁溪東剖面古亭坑層泥岩所含有孔蟲化石之穩定氧碳同位素應用及限制再探

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摘要

古亭坑層主要分布在台灣西南一帶，根據前人研究建立之古地磁-生物地層顯示，本地層應屬於晚中新世至中更新世，其中雖偶夾砂岩層，但大多為泥岩為主，對比於同時期台灣西部麓山帶隻其他地層，推測仍應屬於古水深較深之沉積盆地，且沉積速率快速，化石保存良好，具有潛力成為台灣沉積岩層之重要對比層位。

有孔蟲氧同位素地層自 1950 年代相關分析技術建立以及全球各地海洋岩芯材料的累積，在與米蘭科維奇理論結合後，有孔蟲氧同位素地層所代表之意義已經超越純粹化學地層對比的工具，在新生代以來作為年代地層、環境變化指標等重要性已經透過許多研究加以證實。

本研究根據前人研究古亭坑層中所謂“二仁溪東剖面”，重新發現與再訪了自古亭橋至鹿埔向斜共計 42 個剖面，採集 110 個泥岩樣本，並自其中挑選出保存較為良好的浮游(*Globigerinoides ruber* white, *s.s.*,; *Trilobatus sacculifer* without sac, 7-10 隻，殼體大小皆為>250 μm)以及底棲性(*Cibcidoides wuellerstorfi*,; *Uvigerina* spp. 2-5 隻，殼體大小皆為>250 μm)有孔蟲共計 195 個樣本進行穩定氧碳同位素測試。

結果顯示在大多數的剖面中，浮游性有孔蟲之氧碳同位素落在-2.1 ± 0.4 ‰以及 1.2 ± 0.4 ‰範圍，與西太平洋熱帶地區第四紀紀錄接近，底棲有孔蟲氧碳同位素落在 2.7 ± 0.5 ‰與-1.1 ± 0.4 ‰之間，與全球底棲綜合曲線之結果接近，並且整體隨著剖面年代變化並沒有顯著的長期趨勢。初步結果雖然沒有辦法直接對應到冰期間冰期的週期變化，但整體數值的範圍仍顯示古亭坑層泥岩具有潛力建立更高時間解析度的養同位素地層。

但是在本研究剖面靠近所謂小滾水斷層/背斜區域，浮游與底棲有孔蟲的氧碳同位素均有 4-6 ‰的負偏移，表示此區域具有顯著的成岩作用影響，亦是未來在台灣西南泥岩區進行相關地球化學分析需注意之處。

Morphometric Assessment of Left and Right Coiling Bio-events in the Foraminifera Pulleniatina during the Pleistocene, 2.1-1.7 Ma Interval, Solomon Sea; An Examination of Morphological Variation and Speciation

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Abstract

The impact of both rapid and prolonged changes in environmental and oceanographic conditions on marine organisms has become an increasingly concerning issue given the modern climate crisis. Studying the observations and consequences of regional and global climatic shifts on organisms poses a complex challenge, necessitating multidisciplinary approaches and datasets compiled from fossil materials that extend well beyond the limitations of contemporary sampling alone.

The Plio-Pleistocene boundary globally records an interval marked by shifting oceanic conditions and climatic changes, thought to be influenced by shifts in the Pacific warm pool and East African monsoon around 2.1-1.7 million years ago. This timeframe offers a unique opportunity to examine the morphological response of foraminifera to these changing environments. Foraminifera, protists with hardened, biomineralized skeletons, serve as an ideal model organism for quantifying morphological variation in response to shifting environmental parameters at various temporal and spatial scales.

This study explores a dataset of *Pulleniatina obliquiloculata* from the Solomon Sea's ODP 1115B core. Globally, during the 2.2-1.7 million interval, the species records two distinct coiling direction transitions from dominantly right to left. Despite broad

biostratigraphic implications, the drivers of "left coiling" events are poorly understood. Beyond coiling shifts, morphological variation, both temporally and geographically, has been understudied as well; analyzing how these co-vary is a question of significant evolutionary interest. This study applies a novel morphometric analyses as well as a preliminary 3D CT-scan data towards our analysis. Initial results indicate morphology stability within examined populations prior to, during, and after the L5 coiling event. This suggests coiling variation within a single population rather than speciation events or cryptic population replacements driving observed events.

Anomalous groundwater pressure variations in various depths in the Milun Fault observation system during Typhoon Haikui

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ABSTRACT

Pore water pressure in porous media is sensitive to volume strain that can be used to detect the static and/or dynamic strain induced by earthquakes. Furthermore, fluid is proved to be an important factor in fault activities. Therefore, observation of pore water pressure in a fault system may help understand the mechanism of fluid-fault interactions. Milun Fault is estimated to have a high probability of major earthquake occurrence whereas the Hualien area has experienced numerous earthquake events. An integrated observation system for groundwater variations was thus set in the north segment of Milun Fault. A pressure gauge system with four screen openings and four fiber Bragg grating device with a 200 Hz sampling interval was installed in the Milun well. The setting depths were selected based on the high permeable zones with the consideration of water gas anomalies, core sample analysis, and well logging results. Observation data show step increases in groundwater level in all four depths of the Milun well on September 4th, 2023 during Typhoon Haikui. There is no corresponding earthquake event during this period. The phenomenon of step increases in groundwater level should not come from rainfall recharge due to its inconsistent responses. The seismic data from MiDAS system did not show significant seismic signal but a signal of high strain rate during the same duration. Several earthquake events occurred after the anomaly period might be one of the possibility for the triggering. Are the step increases in groundwater level a signal of earthquake precursor or relative to fault activity? Further investigations are required. **Keywords:** Earthquake hydrology, Groundwater pressure observation, Milun Fault, Groundwater anomaly, Fiber Bragg grating.

Exploring the application of Phasenet-DAS to continuous optical fiber DAS recordings of MiDAS

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We investigate the efficacy of Phasenet-DAS on data collected from two boreholes installed near and across the Milun fault. Phasenet-DAS is a convolutional neural network for picking P- and S-wave arrival times from distributed acoustic sensing (DAS) data; the model we use was trained on surface fiber data in California. The data used covers the month of February 2023, divided into 30 minute segments, bandpassed from (0.01, 0.1, 1) to (10, 20, 30, 40, 50) hz, and then downsampled to 100hz. The data for hole A had 170 channels, and the data for hole B had 122. Both had 4 meter spacing. Phasenet-DAS picked ~16000 events with S-waves, and 65 events with P-waves (often, Phasenet-DAS mislabels P-waves as S-waves). Events were clustered by the presence of a 1 second gap between picks. We compared the picks against the CWA catalog which contained 2119 earthquakes. Of those, there were 450 earthquakes where Phasenet-DAS picked anything within range of expected P- and S- arrivals. There were 48 earthquakes where it picked P-waves within range. Those were all within 60 km of the borehole. Further attempt was made to the surface segments to give more justification to the borehole observations. It is worthy to note that our focus is not on catalog completeness, our objective is to detect and investigate non-catalog events. We explore why some catalog events weren't picked and assess compatibility with surface segments. Phasenet-DAS showcased daily temporal variations in background activity for non-catalog events. Further exploration will delve into these identified non-catalog events, examining their relationship to artificial activities (such as traffic or quarrying) and environmental factors, including activity of small earthquakes, tremors, or storm-related features. Through this approach, we aim to leverage Phasenet-DAS for an initial sorting of the extensive dataset, facilitating the detection of activities aligned with our research interests.

Characteristics of clay minerals from the Milun fault Drilling and All-inclusive Sensing (MiDAS)

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Abstract

The 2018 Hualien earthquake (Mw 6.4), resulting in the Milun fault to rupture and caused hundreds of casualties. Therefore, understanding the composition of the Milun fault zone is of paramount importance for assessing the potential seismic hazard. The Milun Fault Drilling and All-inclusive Sensing project (MiDAS) was conducted in 2020, and three boreholes (A-C) were drilled. In boreholes A and C, continuous cores were drilled to obtain fault-zone materials. X-ray diffraction data (XRD) show that the samples collected from the MiDAS contain quartz, feldspar, and clay minerals such as illite, chlorite, and smectite. In addition, in hole A, the mineral assemblage of altered porphyritic schist is similar to that of the grey gouge. In hole C, the mineral assemblages of the green gouge are similar to those of the grey gouge and dark grey gouge. The similarity of the mineral assemblages between Hole A and Hole C suggests that the borehole core samples collected from 361.8 m to 522.9 m in Hole-A and from 507.9 m to 543.3 m at depth in Hole C can be considered as continuous cores that penetrate the Milun fault. We will conduct optical microscopy, scanning electron microscopy, and XRD analysis to obtain microstructural features and mineral phases of the core samples. In addition, to estimate the temperatures the fault samples have experienced, we will also conduct thermogravimetry analysis (TGA) and heat fault-zone materials to observe their different thermally driven characteristics at various temperatures. The extensive and comprehensive analyses on the Milun fault allow to develop a mineralogical and microstructural reference dataset and may help us to illuminate the structure and evolutionary process of the Milun Fault within this complex structural region.

利用 Double-Beamforming 與光纖地震儀資料探討梅山斷層帶淺部剪力波速度構造

Imaging Shallow Shear-Velocity Structure of the Meishan Fault Zone using Distributed Acoustic Sensing (DAS) Data and Double-Beamforming Method

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摘要

梅山斷層為一條東北-西南走向之右移斷層，1906 年梅山斷層的錯動，造成當時地表破裂由梅山向民雄延伸，破裂總長約 13 公里。透過淺層反射震測，斷層破裂區域顯示了大量橫移斷層所引發的壓縮型開花構造，而民雄至新港間出現大量線性分佈的噴沙、噴水與地裂情形，卻無明顯錯動現象。另外，透過 GPS 資料，柯斯曼等(2014)分析嘉義梅山斷層周遭區域之速度場，發現嘉義新港區域的速度場結果顯示右移斷層特性，推測梅山斷層可能向西延伸 15 公里。2023 年 9 月 5 日，嘉義新港發生芮氏規模 5.5、深度約 8.5 公里的地震，再次引發我們對於嘉義梅山斷層的關注，因此，我們利用新港鄉與嘉義市間的暗光纖，透過 Distributed acoustic sensing (DAS)技術來進行應變資料的採集。DAS

優勢在於能夠沿著光纖路徑，每隔數公尺捕捉應變資訊，使 DAS 陣列具有廣泛的頻寬與高度的波形還原能力，以此提高我們對斷層幾何構造上的解析能力。

為釐清 1906 年梅山地震於民雄-新港區域引起一系列線性分佈的噴沙與地裂情況是否為梅山斷層向西延伸的證據，本研究欲利用 DAS 資料搭配噪聲 double-beamforming 的速度成像方法，分析暗光纖通過區域內的淺層構造、提供該區精細的淺層剪力波速度分佈；又由於暗光纖通過大量噴沙之位置，預期會呈現較低之剪力波波速分佈，藉此建構出梅山斷層延伸位置下的地下構造，以利未來對梅山斷層鄰近構造細節與活動特性有更進一步的瞭解。

Landslide Monitoring with Distributed Acoustic Sensing: The LAMDA project

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Abstract

The LAndslide Monitoring via Distributed Acoustic Sensing (DAS)-inclusive seismic Analysis project (LAMDA) is a pioneer project drilling a 100-meter hole with downhole fiber installed at the scarp of the Lantai landslide to monitor possible movements of the slope using the DAS technique. The large-scale Lantai landslide is a complex deep-seated landslide with multiple fracture/shear zones and aquifer-aquitard layers identified along the depth, exhibiting clear seasonal moving behavior associated with rainfall. The DAS technique that turns the downhole fiber into a dense seismic array every two meters provides excellent resolution to capturing subtle movements or movement-related micro-slip vibrations at various depths over time. With two campaigns in November 2022-February 2023 and October 2023, we identify an active sliding interface at a depth of ca. 21 meters constantly creeping. Together with a surface seismic network of 10 stations covering the crown part of the landslide, we aim to gain high-resolution and deep insight into the dynamics of deep-seated landslides for possible early warning of failure.

Keywords: Deep-seated landslide, Distributed Acoustic Sensing, Downhole fiber, Temporal monitoring

Mineralogical and microstructural characteristics of active fault zone of the Milun Fault, and their implications

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The Milun fault was triggered by the Hualien earthquake (M_w 6.4) and ruptured in 2018. The Milun fault has ruptured in 1951 and is therefore considered to be an active fault with a short recurrence interval. However, the fault-zone characteristics of the Milun fault remain unknown due to the lack of an exposed fault zone. The Milun fault Drilling and All-inclusive Sensing (MiDAS) project was designed to penetrate the active fault zone of the Milun fault and to deploy multiple monitoring systems. Here, we characterize the fault zone from the MiDAS using microanalytical methods, including optical microscopy, scanning electron microscopy, transmission electron microscopy, in-situ synchrotron X-ray diffraction and particle size analysis. The Milun fault zone is sandwiched by the Milun conglomerate in the hanging wall and footwall. The Milun fault zone is characterized by both variable widths of anastomosing clay-rich zones within spotted schists and dark grey gouges. In particular, multiple black gouge layers are observed as either fault veins or injection veins. The mineral assemblages of all samples include quartz, feldspar, carbonates, chlorite, and illite, while graphite and amorphous materials are observed within the black gouge. The black gouge contains reduced-size grains with flow-like structures as well as nanoscale fibrous structures. These observations suggest strain localization and frictional heating within the black gouge. The slip zone of the Milun fault is potentially identified, and its features can shed light on documenting the ancient coseismic events and the underlying earthquake physics.

Application of Distributed Acoustic Sensing in Seismology: A Case Study for the 2022 M_L6.8 Chihshang Earthquake

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Abstract

The Milun fault Drilling and All-inclusive Sensing (MiDAS) project in 2020 successfully drilled into a recent ruptured active fault on the northwestern edge of the Milun Terrace in Hualien, and set up a cross-fault zone observatory with distributed acoustic sensing (DAS) data to serve a long-term monitoring for understanding of earthquakes nucleation, propagation and energy partition. The application of DAS presents unique advantages for earthquake monitoring compared with standard seismic networks: spatially dense measurements with high-temporal resolution. Moreover, the MiDAS network recorded more than 10 seismic events with magnitude > 6 which occurred in eastern Taiwan in 2022. It provides a good opportunity to investigate the source complexity for large magnitude earthquakes by DAS. In this study, we would like to understand the rupture process of the 2022 M_L 6.8 Chihshang earthquake by taking advantage of using the DAS data from the MiDAS project. We apply a deconvolution method by considering a small event in 2022 Chihshang earthquake sequence as an empirical Green's function (EGF) to determine the relative source time function (RSTF) of the mainshock. The RSTF indicates a gross temporal and spatial characteristics of faulting on mainshock. The result of approximated source time function reveals an intriguing feature with high-frequency pattern, which might imply some kinds of fault heterogeneity that would result in abrupt changes in the rupture process, including fault-friction properties and fault geometry. The relative source time function will be a justified reference for our further work on source inversion and dynamic modeling of the 2022 M_L 6.8 Chihshang earthquake. Coupled with dynamic rupture modeling, it might improve our understanding of earthquake rupture dynamics.

綠島的火山地形與地層

Volcanic Topography and Stratigraphy of Lutao Island

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摘　要

位處臺灣東南方的綠島是為呂宋島弧北延的部分，與海岸山脈以及蘭嶼被普遍認為能夠展現島弧火山隨時間與空間的演變序列；綠島提供保存良好的露頭，是探討島弧火山隨弧陸碰撞演變歷史的好題材。鑒此，本研究針對綠島進行地形分析、野外調查同時彙整前人研究之成果；用以釐清火山岩的產狀與分佈，再透過岩象、岩相以及放射性定年分析等資料，剖析綠島的地形特徵並建立火山地層，最後嘗試探討綠島的火山演化歷史。

地形分析顯示，綠島溫泉漁港至綠島機場有東南-西北走向之構造橫跨全島，8 層海階分佈於構造線的兩側，其中東北側的海階較寬廣、層數多，西南側海階窄、層數少；有一殘存的火山錐體地形可於綠島西南側觀察到，暗示東北側之地形較為年輕，西南側之地形較老。綠島火山岩的岩象的鐵鎂礦物含量，隨著時序演進有橄欖石、輝石減少，角閃石、黑雲母增加的趨勢。野外調查顯示，綠島東北側燕子洞至南側龜灣鼻海岸沿線，以數層橄欖石－輝石、輝石－角閃石火山碎屑密度流(PDCs)、火山岩屑崩落(Debris avalanche)、熔岩流(Lava flow)為主。可側向追蹤之火山碎屑岩層的位態顯示，綠島東側以柚子湖為中心，北側呈現 N85° E/30° N，南側呈現 N60° W/25° S，指示綠島東側過去有地形高區存在。柚子湖至海蓼坪一帶可觀察到數個放射－水平排列柱狀節理的含黑雲母熔岩流出露，具火山頸(conduit)的特徵；東南與東北側則分別有含黑雲母的皮里恩式與隱藏式火山穹丘(Pelèean & crypto dome)出露，反應末期岩漿侵入作用；這些火山頸與火

山穹丘截切、入侵至前述的火山角礫岩層。

原於現今柚子湖至海篹坪東側有一火山地形高區，約於 1.5 Ma 左右隨著弧陸碰撞持續擠壓與抬升，使綠島東側地形高區發生裂隙，含有黑雲母的岩漿得以延裂隙上升，形成隱藏式火山穹丘並促使東側發生火山垮塌，綠島西側則未受到明顯影響，得以保存原始地形。

關鍵字:火山地形、火山地層、綠島、北呂宋島弧
Keywords: Volcanic Topography, Volcanic Stratigraphy, Lutao, Northern Luzon Arc.

臺灣東北外海－棉花嶼的火山噴發類型與演化模式

Volcanic Eruption Types and Evolution Model of Mianhua Island, Northeast Offshore Taiwan

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摘　要

「棉花嶼」與彭佳嶼、花瓶嶼統稱為北方三島，為臺灣北部火山活動帶中分布最北的成員，棉花嶼的地貌也未受到人為破壞，火山岩未受到風化保存良好，為探討玄武岩火山噴發行為與模式的良好題材。然而，過去棉花嶼的前人研究多著重於地球化學與放射性定年之研究，鮮少探討火山噴發行為與演化模式之議題。鑑此，本研究首先透過高解析度航照圖進行地形分析，再透過野外調查火山岩之產狀與分佈並進行岩相分析；配合前人研究之資料進行彙整，嘗試重建棉花嶼的火山島噴發類型與演化模式。

棉花嶼的西北部地形平緩，海岸邊有海階發育；東南部地形高聳，有三個近似半圓型的地形分布於此處，同時海岸呈現陡峭且多大岩塊散佈。島上的火山岩可劃分為 5 種不同的岩相，分別為：(1)pTB:橙玄武玻璃化之玻璃質火山灰，偶夾火山角礫岩。掏選度中等至佳，具有正、雙礫級層、平行紋理與低角度交錯層之特徵。為(2)aaL:具有三明治構造(sandwich structure)、斜坡構造(ramping structure)之玄武岩質熔岩流。(3)phL:具有繩狀構造、水平氣孔層之玄武岩質熔岩流。(4)spL：掏選度中至差，具氣孔之不規則火山角礫。(5)Dy:具氣泡構造、冷卻邊緣之侵入岩脈。棉花嶼最底部之層序以的 pTB 岩相為主，;Dy 岩相則截切穿越前兩個層序。

噴發中心位於棉花嶼東南側，噴發型態由淺水轉至陸上環境，噴發強度逐漸

下降至歇止，演化過程如下：早期的 Surtseyan 噴發產生大量低濃度火山碎屑密度流的 pTB 相火山噴發物，形成棉花嶼的基底。隨相對海水面低於火山噴發口，火山轉變為溢流式的夏威夷式噴發為主，產生 aaL、phL 相熔岩流堆積物並形成島的主體；同時在東南側形成 3 個噴濺火山錐(spatter cone)由 spL 岩相堆積物組成。隨時序演進，小規模的噴發活動與岩漿通道(conduit)上湧，使火山體發生垮塌，產生現今棉花嶼東南側的火山垮塌地形。

關鍵字:
棉花嶼、瑟西洋式噴發、夏威夷式噴發、渣狀熔岩流、繩狀熔岩流
Mianhua Island, Surtseyan type eruption, Hawaiian type eruption, a’a lava flows, Pāhoehoe lava flows

臺灣澎湖本島地區之熔岩流構造、類型與流變學特徵

The lava flow textures, types and rheological characteristics of the Penghu Island, Taiwan.

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摘　要

玄武岩質熔岩流具溫度高、黏滯度低的流變學特徵，相對較酸性的熔岩流不僅有著較高的流動性，更有機會保存熔岩流中的構造，判讀熔岩流構造、冷卻節理之形式，有助於我們理解與釐清熔岩流的遷移、堆積與冷卻的過程，更能應用於進行熔岩流細部對比工作。

澎湖群島位於臺灣海峽南部，由 90 座地勢平緩、大小不一的島嶼所組成，這些島嶼主要由玄武岩質熔岩流間夾少部分火山碎屑岩與海相沉積岩互層所構成。其中，玄武岩部分保存有豐富且具特徵性的熔岩流構造，以及各式之冷卻節理。然而，在針對澎湖地區的相關前人研究之中，多數的研究著重於岩石地球化學、放射性年代學、化石與沉積環境與沉積體系、大地構造等研究；鮮少有研究深入探討熔岩流構造的種類與意義，並嘗試解釋其背後之火山學之意義。鑑此，本研究透過野外調查重新檢視澎湖本島地區之玄武岩熔岩流的產狀特徵，同時配合彙整前人研究之資料，進一步探討本地區熔岩流的遷移、堆積與冷卻歷史。

澎湖本島地區之熔岩流可觀察到完整 Entablature－Colonnade－P.P.C 之熔岩流序列變化，普遍具有典型的 S-type & P-type Pāhoehoe 熔岩流特徵，如：氣孔柱(vesicle pipe/cylinder)、水平氣孔層(horizontal vesicular sheets)、圓丘狀頂面等，亦可見鑿鑄痕(chisel marks)、戰冠(war bonnet)、柱狀節理(columnar joint)、鬼節理(ghost joint)等冷卻節理構造。馬公金龍頭活動中心西北側海岸則可見 P.P.C 序列中的枕狀熔岩流(pillow lava)。透過產狀進一步區分，則可將本區之熔岩流區分為

Lft、Lfc、Lfb、Lp 四個岩相，分別指示熔岩流的上、中、下各部位。本研究之熔岩流產狀觀察與岩相分類之成果，可基於澎湖地區詳盡之生物地層時間之框架下，進一步探討詳盡探討本區域的熔岩流分佈與對比。

關鍵字:
澎湖群島、繩狀熔岩流、熔岩流構造、冷卻節理
Penghu Islands, Pāhoehoe lava flows, lava flow textures, cooling joints

從沉積物紀錄解析台灣北部大屯火山群晚期火山活動

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大屯火山群為台灣本島唯一活火山，也是北台灣公眾安全的潛在威脅。目前大屯火山群1萬年內的噴發紀錄只有兩筆，皆在七星山周邊，其中一筆紀錄來自紗帽山邊一處紋層泥露頭的火山灰層。本研究分別以礦物相/岩象、火山灰組成及顆粒形貌分析等方法分析該處火山灰樣本，以瞭解大屯火山更新世末期火山活動特徵，如大屯火山噴發行為、型式與規模。

過去文獻以此火山灰層上下層位放射性碳定年推論大屯火山曾在17,000-13,000年前發生蒸氣噴發活動（Belousov et al. 2010）。本研究根據沉積物組成、岩象組構、顆粒形貌、熱液礦物學、共沉積矽藻等證據，認為此處火山灰並非原生火山灰，並提出兩種可能，第一種可能是火山低溫熱液蝕變產物的再積性沉積物，本身並無火山噴發活動的意涵。第二種可能是再積性火山灰，沉積物母質可能是同噴發（syn-eruptive）來源的再沉積火山碎屑堆積物（resedimented volcanoclastic deposits），或是後噴發（post-eruptive）來源的火山源沉積物（volcanogenic sedimentary deposits）。如為再積性火山灰，由於樣本蝕變礦物群的反應流體穩定酸鹼度範圍並不一致，不是同噴發產物的特徵，較可能是後噴發產物，也就是多期噴發產物經搬運混合的火山源沉積物，它的原始母質噴發年代老於目前堆積層位所得的放射碳年代，無法探討原始火山活動年代意義。故本研究建議，探討年輕火山碎屑沉積事件時，如無詳細岩象觀察佐證，不宜過度推論解釋其火山噴發活動年代意涵。

大屯火山溫泉水的地球化學成因研究與相關岩漿活動監測初步結果

A preliminary study of the geochemical genesis of hot spring waters and indicators for monitoring underlying magmatic activities in Tatun Volcanic Group

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本研究配合大屯火山監測總計畫，於本區域內選取溫泉分布點，記錄溫泉水主要元素、微量元素以及同位素的時間序列變化，嘗試瞭解大屯火山區各溫泉的地化演化意義和找出可能的火山岩漿活動指標。採樣點包括位於沉積岩區的地熱谷、大峰、磺港，位於火成岩區的龍鳳谷、湖山、冷水坑、七股、大油坑、八煙、四磺坪，其中水質屬於中性的為湖山、冷水坑、磺港，其餘為酸性水質，屬於還原態的為冷水坑、磺港，其餘屬於氧化態。樣本之採樣時間為 2020 年 5 月到 2023 年 5 月，主要元素顯示水質穩定，氫氧同位素顯示主要成因為天水蒸發，但部分可能有較多的岩漿氣體或水岩反應來源，鍶同位素 $^{87}Sr/^{86}Sr$ 比值顯示沉積岩區的溫泉水受到不等比例的來自沉積岩的 Sr 的和火成岩的 Sr 的混合；以 K, Na, Mg 繪製的三角圖判釋出本區溫泉水皆未達水岩反應化學平衡，暗示本區溫泉水在水層的滯留時間較短；時間序列的分析包括 pH、TDS、Cl、 SO4、Cl/SO4、B、B/Cl 等等，初步看隨時間並無明顯的變化；其他地球化學的觀察包括：火成岩區的酸性水有較高含量的磷(0.1~10ppm)且磷與微量/高價元素有很好的正相關，應是代表磷酸鹽類礦物的水岩反應結果，而地熱谷和大峰具有高的砷含量分別為~5 ppm 和 1.9 ppm，在湖山、大油坑和磺港也有較高的砷含量，火成岩區的砷和主要元素、微量元素有正相關，而沉積岩區砷僅和微量元素存在良好相關，其來源須進一步探討。在嘗試辨識岩漿活動方面，觀察到 B/Cl 比值仍是一個岩漿揮發份來源的很好的指標，例如在七股 B/Cl 比值~0.013 代表火成岩的比例，對應到水岩反應為主的水質型態，而大油坑 B/Cl 比值~0.003 則指示岩漿氣體來源為主的結果，目前以 B/Cl 比值作為監測岩漿來源的指標之一，連同其餘的揮發性化學組成例如 Cl, S (SO4)等等的變化。本研究也嘗試探討大屯火山區溫泉水中微量元素的變化控因，例如砷、鉛、鈾、稀土元素等；預期未來可透過地球化學熱力學模擬來進一步解析和探討各溫泉水形成的演化因素。

紗帽山近期噴發年代: 15000年或1370年?

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摘　要

地球物理資料顯示大屯火山群之下在約8-20公里存在岩漿庫(Lin, 2016; Huang et al., 2021)，當火山活動及伴隨災害，對於約700萬人口的大台北地區而言是重要議題。為釐清大屯火山噴發年代，本研究結合Ar-Ar定年、鋯石U-Th/Pb不平衡定年及鋯石U-Th/He定年分析紗帽山噴發年代。

過去紗帽山定年有Ar-Ar定年(0.23Ma)、鋯石核飛跡(0.23Ma及小於20Ka)、K-Ar定年(0.3Ma)及Zellmer et al.,(2015)利用U-Th-Ra定年得到紗帽山的噴發年代約為1370±11年，但過去分析方法受限於儀器精度或方法限制，年代不易確定，為釐清此紗帽山噴發年代，本研究利用高解析度的Ar-Ar定年、鋯石U-Th/Pb不平衡定年及鋯石U-Th/He定年方法分析此噴發年代， Ar-Ar定年顯示噴發年代為15±6.3Ka、鋯石U-Th/Pb不平衡定年為23.5±2Ka、鋯石U-Th/He年代為15Ka，其中鋯石U-Th/Pb不平衡定年為23.5±2Ka為鋯石形成年代，代表深部岩漿庫年代，而16.3±4.9Ka為噴發年代。 此結果與Lee (2017)利用鋯石核飛跡年代得到年輕於20Ka，Belovsou et al.,(2010) 推測紗帽山年代為13-16Ka，並與Zellmer et al.,(2015)分析斜長石不平衡定年的18±1.3Ka等結果近似。

北臺灣大屯火山群七星山岩漿庫行為之研究

Magma chamber behavior study of Chihsingshan in Tatun Volcano Group, Northern Taiwan

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摘 要

七星山亞群為大屯火山群中的一個亞群，主要山峰有:七星山、白雲山、燒庚寮、竹篙山、紗帽山及七股山等。根據前人研究，七星山可分為三期不同岩性之岩漿噴發(分別為紫蘇輝石角閃石安山岩、含角閃石兩輝石安山岩、兩輝石角閃石安山岩)。七星山上有東西兩側各約四個噴發爆裂口的裂隙帶，陽管處在2021 年執行的計畫中，完成了東側四個井的鑽探，分別接鑽至下方火山岩岩心。本研究欲利用此岩心中火成岩之各項資訊，探討七星山下方岩漿庫之行為特徵。

本研究針對七星山東側之蒸氣噴發爆裂口之火成岩岩心進行採樣，分別於S1、S3 兩個鑽井點取樣，其中 S1 取深度 4.3-4.6 m、9.4-9.8 m、11-11.4 m, S3取深度 5.7-6 m、7.4-8 m 共五段長度進行研究。將岩心製成岩石薄片(岩象學觀察)，確認其中所包含之礦物種類，將需要做礦物化學的礦物鎖定在斜長石、角閃石、輝石。製作岩石靶進行掃描式電子顯微鏡 (Scanning Electron

Microscope，SEM)與電子能量散射分析(Energy-dispersive X-ray spectroscopy，EDS)(目的為觀察礦物外型及化學組成)，將SEM-EDS所得到的結果，利用電子微探儀(Electron Probe Microanalyzer，EPMA)對礦物進行化學成分的定量分析，礦物化學數據藉由前人文獻中的經驗公式對斜輝石進行地溫計算、角閃石進行地壓計算、斜長石觀察其An值與Mg擴散速率之間的關係，了解此岩漿約待在地下多久的時間及有無新岩漿來源補充。並進行全岩主要及微量元素地球化學分析，比對前人的地化特性。七星山全岩的地球化學成分均一，鈥同位素值變化極小，顯示岩漿源區單一。藉由計算結果得知，此岩心中的礦物生長環境在地下6-14公里之間的區域，晶體開始生長時的溫度在1160℃～1200℃間。將壓力所得之深度與黃信樺(2021)進行比對，發現有區域重疊之處，Mg擴散速率則可得到此岩漿在噴發之前，於岩漿庫停留了約2000年的時間，期間岩漿源約補充2次。

關鍵字：岩象學、礦物化學、全岩地球化學、七星山

高雄寶來地區地熱潛能探勘成果簡介

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摘　要

臺灣位於板塊碰撞聚合帶，島上存在超過 150 處的溫泉與地熱徵兆區，擁有地熱發電開發潛能的先天優勢，對於我國能源自主化及多元化的目標來說，運用地熱發電能做為基載電力（base-load power），是不可或缺的重要選項，若能妥善開發地熱相關產業，勢必能促進我國再生能源最大化，達成 2050 年能源轉型、淨零轉型之願景。

寶來地屬地震頻繁區域，其鄰近地區的水文循環與淺層地熱能萃取，受控於斷層及大型破裂帶的分佈；此潛勢區雖具地熱開發潛能，但在全臺地熱調查區中仍屬地熱探勘資料較缺乏的區域，至今尚未有較深的地熱探勘井，且溫泉水質的地球化學分析資料亦較無全面性與系統性的分析。

本團隊在寶來地區根據前人研究提出兩種可能的地質及水文模式，一、只考慮荖濃溪西側的潮州斷層，整體水文循環，由潮州斷層破裂帶系統控制；二、加入考慮美瓏山斷層為東側的重要破裂帶，則潮州斷層以東之水文將被區隔成兩個主要的循環系統。本研究透過地質調查、地球物理探勘，針對裂隙系統及地下地質進行調查，並配合野外調查與溫泉水化學分析進行地熱潛能評估，初步建立變質岩區的探勘模式與寶來地區之三維地熱地質概念模型。

綜合地質、地物、地化及二維水流場模擬成果，可清楚辨識寶來地區的地下水循環系統在美瓏山斷層兩側有顯著的差異性，顯示水循環模式受控於潮州-美瓏山雙斷層模式：天水由中央山脈高山區補注滲入地下深部，通過地溫梯度加熱，經由與潮州斷層相關的深部裂隙帶流通，因受到美瓏山斷層面的阻隔，水團的移動分裂成斷層上盤與下盤的不同途徑，各別依循與潮州-美瓏山斷層相關的裂隙帶往上遷徙；至近地表處，受到新期構造活動帶的影響，在有優勢裂隙的地區，淺部的裂隙提供天水補注，與深部往上遷徙的熱水團混合；另一方面，在美瓏山斷層與潮州斷層間，溫泉井水質則主要呈現深循環或地層水信號。未來經由鑽井探勘將可更進一步確認破裂帶與地下水循環模式，以精準評估可供開發之地熱蘊藏值。

臺東鹿野溪下游地熱區古流體溫壓及三維應力場之探討

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摘要

台東縣延平鄉鹿野溪，地處中央山脈的紅葉地區，近年來是國家發展地熱產業的重點區域之一。根據地質調查結果指出，鹿野溪出露的紅葉層岩性大致為黑色板岩間夾薄層砂岩，綜觀鹿野溪沿岸有相當多溫泉，調查其地質構造主要以發達的板劈理為主，常伴隨急折帶的出現，並且有正斷層出露，正斷層之裂隙多伴隨石英礦脈發育與熱液流出。受到造山作用影響，岩石受力發育出裂隙，使含有二氧化矽的流體充填其中，由於石英脈發育時，二氧化矽流體液壓至少要達到最小正應力，才能將岩體撐開，因此藉由測量石英脈生長方向與石英脈中所含的液包體之均化溫度和冰融溫度等資訊，可以推估礦脈形成時溫度液壓等資訊，以進一步用於探討現地過去的應力場問題。本研究利用液包體分析與礦脈位態統計的方式進行石英脈生成時之地溫梯度計算。經構造與石英脈截切關係分類，新一期石英脈主要位態分布為西北－東南方向以及東北－西南方向，兩者截切關係又以西北－東南向截斷東北－西南向者，證實西北－東南向的石英礦脈為較後期生長者。利用礦脈位態統計進行三維應力場方向判斷，結合液包體微溫度測定分析與其拉曼光譜封存壓力計算所求得的溫壓資料，估計出應力數值與這些石英脈的發育溫度與深度，進而估算研究區的古地溫梯度。根據初步的成果，石英形成的溫度約在 300℃至 368℃，壓力有待進一步量測換算。

地熱發電依靠地下熱能來發電，這些熱能通常透過提取地熱儲層獲取，因此水壓與應力場的變化對地熱井的生產效率有極大的影響，較高的液壓可以提高地熱流體的流速，從而提高發電廠的效率和輸出，利用場址鄰近區域岩體中較後期形成之礦脈的液壓與地表鑽井求得之液壓數值進行比對，並且比較此處溫度與液壓是否有衰減的情況，進一步評估其開發潛能。應力場則是影響岩體中裂隙和斷層的形成方向，裂隙縫與斷層是熱水的良好通道，古應力場可能促使了地熱通道的長期穩定，然而其不一定與當今條件相符，由於構造活動或其他地質事件影響，導致應力隨著時間的推移而產生改變，透過量測應力場的變化，確定應力方向、大小和空間分佈的異同，藉以評估該地建廠發電的可行性。

關鍵詞：鹿野溪、液包體、拉曼光譜分析、石英礦脈、地熱開發

大屯火山群於 1984-2024 年間衛星監測之地表溫度及其與地震規模之相關性研究

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摘要

大屯火山群(Tatun Volcanic Group; TVG)是台灣島上唯一的一處活火山，其最近一次噴發距今約 5,500 年前。前人諸多研究顯示 TVG 仍然具備再次爆發的可能性，一旦火山爆發，會直接影響波及約 700 萬人口的台北大都會區。因此，大屯火山群未來噴發評估研究是一個至關重要的任務及挑戰。衛星感測器偵測到的火山地表溫度(Land Surface Temperature; LST)可反映出地下熱源的熱狀態，有助於了解活火山的地下岩漿過程及途徑。當岩漿和火山流體從深處輸送到地表時，通常會觸發生成淺層的火山地震。因此，地表溫度和地震規模都是研究活火山的關鍵參數。本研究根據 LST 和地震規模之觀測數據來調查 TVG 的火山噴發潛能狀況。首先根據 TVG 近四十年(1984-2024)的地表溫度來檢視其地熱狀態。美國國家航空暨太空總署(National Aeronautics and Space Administration; NASA)運營的陸地衛星(Landsat)所搭載之熱感測器從 1984 年開始監測全球陸地表面溫度，我們使用這些監測資料以了解 TVG 過去和當前的地熱活動模式以及未來的趨勢；同時使用台灣中央氣象署(Central Weather Administration; CWA)所提供的地震記錄以檢索 TVG 三十多年(1991-2024)的火山地震規模時間序列。綜合衛星 LST 及地震觀測網地震規模時序資料我們比較分析 TVG 地表溫度和火山地震規模的時空分佈，以探究 TVG 過去和目前的火山活動模式以及未來的發展演變趨勢。研究結果顯示 TVG 四十年來 LST 時間序列呈現非線性上昇趨勢。意涵該火山地下熱源的非穩態性質(Non-steady-state)。另外，近四十年的 LST 時間序列和三十多年的地震釋放能量時間序列趨勢呈現高度相似性，說明了地表溫度與火山地震釋放的能量呈現明顯的正相關性，從而可驗證地表溫度與火山地震之間相關聯的假設。

關鍵字：大屯火山群 (TVG)、衛星觀測、陸地衛星(Landsat)、地表溫度 (LST)、地震規模、集合經驗模態分解 (EEMD)

花蓮瑞穗地區地熱鑽探調查分析

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摘　要

本文主要進行花蓮縣瑞林地區之GSMMA-RS-2之自噴井況及井測結果討論，初步探討留點溫度計隨鑽探進尺量測結果與鑽探完成後之PT井測成果比對，前者之量測溫度大致低於後者，且淺部差異大於深部，推測後者可能因深部高溫流體向上噴出導致淺部岩體增溫，致使PT井測量測之溫度高於該深度實際環境溫度，而前者因隨鑽探進尺做溫度量測，淺部岩體未受深部高溫流體影響而增溫，其量測溫度較能反映該深度實際溫度，較有利於與其他調查資料比對與分析解釋。

花蓮瑞林-紅葉地區地熱資源驗證與再探

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摘 要

因應全球氣候變遷以及政府推動能源轉型之政策，地質調查及礦業管理中心提出加速全面性地熱資源調查及資訊供應相關計畫，目的即為打造國家未來需要之綠色能源、促進環境永續的綠能基礎建設。進行我國地熱潛能區之基礎探勘，利用新興科技擴大探勘範圍及深度，以掌握地熱資源的基礎地質資訊，並彙整國內各單位進行的地熱探勘資料，為地熱潛能區探勘資訊整合平台，提供有意投入地熱開發者能掌握地下地質資訊，以降低地熱開發前期之探勘風險，及縮短地熱開發時程。並於 110-111 年度，在花蓮縣瑞林-紅葉地區執行進一步探勘，包含：地表地質調查、大地電磁探測、地動觀測以及地球化學分析等調查方法。整合蒐集過去文獻資料與本計畫的調查資料，提出瑞林-紅葉地區的地熱地質概念模型。研究區域內最大的儲熱構造，有兩種可能：(1)石英雲母片岩中的裂隙發達的岩體，上覆較不透水的蓋層(可能是基性岩體片岩)，含有高液壓的熱水(深循環地熱)；(2)是快速掘升的高溫壓熱岩體本身所提供的高地溫梯度岩石「乾熱儲集層」(淺循環地熱)。這兩種可能的解釋，還需要再進一步的驗證。

112 年度於計畫區域內執行地電阻影像探測，R1 測線位於內溫泉，通過瑞林溫泉露頭以及地礦中心瑞穗 2 號井預定井位。R1 測線探測里程 600~1120 公尺下方有一低阻帶，經鑽井驗證為一高溫高壓之熱儲層。透過瑞穗 1 號井、瑞穗 2 號井的驗證得知，在井下約 250~500 公尺左右有一層高壓熱儲集層。鑽井過程遭遇高溫壓湧井與井噴現象，使得取心鑽進作業難度提升。規劃續鑽瑞穗 3 號井，已確定在內溫泉區域的地熱資源範圍與潛能。

關鍵字：瑞林-紅葉、地熱、鑽井、潛能評估
Keyword: Ruilin - Hongya, Geothermal, Drilling, Potential assessment

臺東紅葉地熱區地熱資源調查與潛能評估
Regional Geothermal Exploration and Potential Assessment of Taitung Hongye Geothermal Area

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摘　要

臺東紅葉地熱潛能區位於臺東縣延平鄉，是近年地熱探勘重點調查區域之一。為了掌握潛能區的地熱資源，本研究藉由地熱地質調查、大地電磁探測以及流體地球化學分析等多種地球科學探勘技術。其中，地熱地質調查包含有線形判釋、應力分析及裂隙量測，提供熱水通道的位態相關資訊；經由大地電磁探測獲得三維電阻模型，可作為地熱構造及熱水通道的重要指標；藉由分析地熱流體之組成成分及氫、氧、氦同位素，解析熱液來源與特性。綜整上述地表地熱調查成果及前人文獻資料，建立臺東紅葉地區三維地熱概念模型。臺灣東部受板塊斜向碰撞，尚存高溫餘熱的火成岩體，有可能受推擠至淺部地殼，而西北方向推擠的壓應力影響，在臺灣東南區域深部，則發育出深切地殼的北東或北北東方向及東北方向的剪切帶，這些剪切帶有可能成為深部熱液向上移棲的通道，或地熱流體在深部側向移棲的管道。而近期因地殼快速抬升，使高溫岩體上升至淺部地殼，同時發育出西北向及南北向的張裂構造，則成為天水加熱及熱水上湧至淺部的儲存空間。深部與淺部構造交織出棋盤狀結構，蘊量出東部地區龐大的地熱潛能。

中文關鍵字：臺東紅葉地熱潛能區、地熱地質調查、流體地球化學分析、大地電磁探測
英文關鍵字：Taitung Hongye potential geothermal field, geothermal geological survey, magnetotellurics exploration, fluid geochemistry analysis

The geochemical signatures for geothermal potential in Baolai area, Kaohsiung

寶來地熱潛能區的地球化學特徵

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南橫公路西段荖濃溪及其支流溪谷的地區內，有多處溫泉分佈，其中大多集中在荖濃溪的支流寶來溪河谷附近，因此被規畫為寶來地熱潛能區。此區域位於台灣西部麓山帶與中央山脈之交界，屬於地壓型地熱型。該區域地質以石洞層為主以及部分角板山時期部分出露的玄武岩，附近主要的構造包括東北一西南方向的土壠灣斷層及美壠山斷層。根據紀錄，八八風災後多數溫泉露頭已被掩埋。為了解寶來區溫泉的分佈特性，配合地熱潛能區的地質調查，本研究針對寶來區域的溫泉進行地球化學調查。本次調查主要針對溫泉井及現存溫泉露頭，包含美崙山水井、美崙山白泉、美崙山棕泉、寶來溫泉公園新井、寶來溫泉公園舊井、國蘭河邊井、石洞、七坑、十坑、復興溫泉進行採樣。調查內容除了現地水溫、酸鹼度、導電度的測量，也進行了各種地球化學的特徵分析，包含溶解無機碳濃度及碳的同位素，溶解的有機碳濃度，陰、陽離子，水的氫、氧同位素，硫酸根及硫化氫的濃度，以及氦同位素，以了解各個區域溫泉的地球化學特性及其來源。

現地水溫的範圍在 27 到 89 ℃ 之間，酸鹼度的範圍在 6.8 到 8.7 之間，導電度的範圍在 1.9 到 18.7 ms 之間，氯離子濃度範圍在 0.082 到 102.1 mM 之間，氯離子濃度範圍在 0.019 到 0.211 mM 之間，氦同位素的範圍在 0.5 到 1.1 Ra 之間。未來將配合其它地質調查的結果，進行分區的討論，以探討不同地域上的分佈是否會導致地球化學特性的差異並進一步評估其作為地熱發電的潛力。

Interpreted 11-6 Ma age of Exhumation history in the subduction channel of the Yuli Belt, Taiwan

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Abstract

Our study provides a new insight into the Cenozoic Yuli metamorphic belt in Taiwan, one of the youngest high-pressure (HP) terrains around the world, focusing on its metamorphic ages, stages, microstructural fabrics, and exhumation mechanisms. We carried out field surveys of well-preserved epidote-amphibolite schist outcrops along the Mayuan River in Juisui and conducted microstructural analyses using microscopy and SEM-EDS, coupled with EPMA to analyze the chemical compositions of amphibole and phengite minerals. Additionally, two different grain sizes (0.18mm and 0.25mm) of phengite were conducted the $^{40}Ar/^{39}Ar$ step heating dating to determine the metamorphic age.

Field observations highlighted S_1 as the primary foliation, shallowly dipping to the northwest or northeast in the Mayuan River area. We identified five stages of metamorphism, ranging from prograde to retrograde (subduction to exhumation): 1) S_0, with rotated stubby subhedral phengite(Ph); 2) S_1, with Ph ± Ep ± Calcic-Amp; 3) S_2, Ph ± Ep ± Calcic-Amp ± Chl; 4) S_3, with Ph ± Calcic-Amp ± Ttn ± Ab; and 5) post-S_3 phengite growth. Amphiboles showed zoned compositions indicative of both "clockwise" (high-T to low-T) transitioning from Pargasite through Edenite/Mg-Hb to Actinolite, Glaucophane to Winchite to Actinolite. The $^{40}Ar/^{39}Ar$ dating revealed an age spectrum at 10.7±1.6 Ma, 10.4±0.5 Ma, 8.8±0.6 Ma, 8.9±1.9 Ma, and 11.0±0.7 Ma, suggesting cooling post-subduction at estimated closure temperatures of 410-420°C. An inverse isochron and age spectrum indicated a minimum age of 6.8±2.84 Ma, likely representing a recrystallized age during exhumation.

This study reveals the P-T-t path of the epidote-amphibolite schists in the subduction channel from subduction to exhumation. However, the kinematics of the high-pressure rocks during exhumation remain debated. Our results indicate that the Yuli belt began exhuming before the arc-continental collision.

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Finite Strain Pattern inferred from AMS across the Southern Portion of the Central Range, Taiwan

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Abstract

Taiwan orogen is a classical mountain belt resulted from on-going arc-continent collision between the Eurasian Plate and the Philippine Sea Plate. During the mountain building period of Taiwan Central Range, multiple cleavages were superposed on the former cleavages, leading that the cleavage across entire Central Range displays fan-like distribution. Stretching lineation also rotates from orogen-normal to orogen-parallel orientation from west to east across the Central Range. These observations of orogen-related structures bring up the research question: What are the magnitudes and orientations of multiple strain ellispoids of Taiwan Central Range? Previous studies have utilized pyrite pressure shadows as strain marker to estimate the magnitudes and orientations of the incremental or finite strain. In this study, we depict the finite strain pattern inferred from magnetic fabrics across the Central Range, including the western slate belt, Tailuko belt, Shoufeng fault, Yuli belt and eastern slate belt along the South Cross-Island Highway, Taiwan.

Anisotropy of Magnetic Susceptibility (AMS) is an efficient tool to analyze the finite strain and characterize tectonic petrofabrics. AMS experiments measured the principal directions and values of magnetic susceptibility ellipsoid and further evaluated the degree of anisotropy and ellipsoid type. Our preliminary results include 3 key points: (1) The magnetic fabrics inferred from AMS are consistent with petrofabrics from field data. The stretching lineation orientation is also consistent with the maximum magnetic susceptibility axis (K1). (2) The AMS results across one mesoscale shear zone outcrop indicate that anomalous high values of corrected anisotropy (Pj > 1.4) could reflect the regional high-strain zone. (3) Maximum magnetic susceptibility axis (K1) rotates from orogen-normal to orogen-parallel from west to east across the Central Range. (4) the Pj values decrease gradually from west to east across the Central Range.

臺灣東部米崙臺地珊瑚礁、米崙溪的構造控制: 全新世變動的抬升速率

Tectonic controls of coral reef and the Milun River in the Milun tableland, eastern Taiwan: Variable uplift rate through Holocene

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Abstract

Taiwan is located within the collision boundary between the Philippine Sea plate and the Eurasian plate. The Milun fault is one of the most active faults with the shortest return interval of 70–80 years in Taiwan, and ruptured in 1951 and 2018. The Milun tableland was elevated by the Milun fault, and there were few studies with little attention to the interplay between tectonic uplift and coral development. This study attempts to understand history of coral development, the Milun River migration, and tectonic uplift of the Milun tableland. We performed field surveys, measured the precise elevation, and analyzing thirty-four ^{14}C dating samples. The results indicate that an uplift rate of 1.0 mm/yr during 8000–4400 yr BP, but a higher rate of 6.9 mm/yr during 4400–0 yr BP. The corals grew in a catch-up mode during 8000–6150 yr BP, but in a give-up mode during 6150–0 yr BP. The submarine Milun River meandered through the north tableland during 6150–4500 yr BP, and passed through the middle tableland during 4500–2100 yr BP. After 2100 yr BP, the Milun River migrated into the present route due to elevation of the tableland. This is the first study systemically analyzed tectonic control about the Milun fault, and revealed the seismic history of the highest hazard probability fault by coral growth and river migration.

台灣與菲律賓 Mindoro 造山帶的比較與對比

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台灣與菲律賓的 Mindoro 島在 30Ma 前同樣位於歐亞大陸邊緣，歷經中生代到始新世的張裂環境，30 Ma 開始南中國海開裂，在 15Ma 之時，Mindoro 與 Palawan 大陸地殼向南飄移，在 15Ma 附近位移到現今位置，新生代以來台灣與 Mindoro 島又歷經中新世以來的造山作用。
在地質上 Mindoro 造山帶與台灣島的地質類似有中生代基盤與始新世的張裂盆地，恰位於南中國海洋板塊的北側與南側，在 Mindoro 島上我們結合露頭與沉積物的鋯石核飛跡定年，顯示最老癒合年代約 7Ma，此外在造山帶東緣最年輕的花崗岩為 14Ma，此花崗岩鋯石的 U-Th/He 定年與磷灰石定年顯示為 6-7 Ma，顯示此時急速隆起，這些資料顯示 Mindoro 造山帶開始時間與台灣近似約在 6-7Ma 近似。此時間也與菲律賓海板塊隱沒於菲律賓變動帶，所伴隨的島弧岩漿開始活動時間近似。由於兩個造山帶的造山時間相似且菲律賓海溝東側島弧岩漿開始時間也近似，我們認為此與菲律賓海洋板塊在約 8Ma 之後轉為西北運動，導致歐亞大陸板塊邊緣開始隱沒，因此兩個造山帶形成時間近似，同時伴隨在菲律賓海溝東側形成島弧岩漿。

兩個造山帶的故事
-台灣與民都洛島
台灣島和民都洛島位於馬林納河的南北兩端
海溝，這兩個造山帶都是歐亞大陸邊緣變形的結果
盤子。 比較兩個造山帶的折返歷史使我們能夠討論其機制
兩個造山帶的造山活動。
在台灣造山帶，造山的時間大約從 1997 年開始。 6-8 Ma，可以
使用 ZrnFT、Ar-Ar 和前陸盆地發展的時間確定。
對於民都洛島，我們結合 ZrnFT、ApaFT 和 ZrnHe 來限制
挖掘。 它顯示最古老的 ZrnFT 年齡約為 10 歲。 6-7 馬。 我們進一步限制最新階段
裂谷大陸地殼中花崗岩的年齡約為。 13Ma 表示碰撞應該晚於
這個年紀。 此外，花崗岩的 ApaFT 和 ZrnHe 年齡約為 6Ma 推斷快速冷卻
年齡與地區 ZrnFT 日期一致。 這些數據暗示了山的時間
民都洛造山帶的建築大約是。 6-7Ma，與台灣造山帶相似。

Exhumation history of the Mindoro, Philippine and its implication to mountain building process

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Abstract

The Mindoro orogenic belt results from the collision between the Palawan continental crust and Luzon Arc. In this study we report the zircon fission track ages to identify the timing of rapid exhumation of Mindoro orogenic belt.

The NNW striking East Mindoro fault (EMF) separates the mountain belt and Luzon arc block. The highest mountain reaches to 2500m on hanging wall of the EMF. In the western side of the EMF the mountain belt can be separate into two blocks by NW trending Mindoro suture zone. To the north and south are Mindoro block and north Palawan block, respectively. The Mindoro block is major comprised of unmetamorphic Eocene strata and Mindoro metamorphic complex. The oldest zircon reset fission track ages shows 5-6 Ma in eastern and western side of the Mindoro metamorphic complex which infers the timing of rapid exhumation since ca. 6Ma which indicate the timing of collision between the Palawan block and Luzon arc.

Introduction

The Mindoro orogenic belt is result from the collision between the Palawan continental crust and Philippine Mobile zone (Yumul, 2009). When opening the South China Sea the Palawan continental crust was drifted to present position and then collided with the Philippine Mobile zone that results in a regional metamorphism and ca. 150 km length mountain belt. (Fig.1). The earthquake data shows the oceanic crust of South China Sea is high angle dipping and collide with the Philippine Mobile belt (Fig.2).

Yumul et al., (2009) Indicated there were at least five collision and accretion events that occurred in central Philippines. These include: (1) The accretionary sequence (Permian to Cretaceous)exposed in Busuanga, Calamian Island Group which formed when Palawan was still part of mainland Asia; (2) The southward translation of Palawan resulted into its collision with an oceanic fragment (Palawan Ophiolite Complex); (3) Regional correlation studies suggest that the Lubang– Puerto Galera Ophiolite in central Mindoro had been emplaced during the Oligocene; (4) The Cretaceous Mangyan Ophiolitic Complex was emplaced during the Cretaceous-early Tertiary period; and (5) The Palawan microcontinental block and Philippine mobile

belt collided during late Early Miocene to early Middle Miocene resulting into the emplacement of the Ophiolitic Complex.

The last stage of collision resulted into metamorphic complex exposed and over one thousand meter mountain build in Mindoro. The Pliocene Punso conglomerate was developed in southern part of the Mindoro which considered as the evidence of timing of collision (Yumul et al., 2003; 2009, Karig, 1983; Sarewitz and Karig,1986). However the Punso conglomerate only observed in southern part of the Mindoro island and there is no evidence to identify the timing of exhumation of metamorphic belt in northern Mindoro. In this study we will conduct the low temperature thermochronology dating to reveal the exhumation history of the Mindoro island. There is three sets of ophiolites in central Mindoro (Yumul Jr et al., 2003), the Mangyan Ophiolite was considered as the originally collision suture zone of PMB. The Puerto Galera Metaophiolitic Unit was result in the collision of PMB and PCB during early Miocene. Amnay ophiolite in southern part of Mindoro could be consider as the collision between PMB and PCB during Late Miocene (Fig.3).

Fission track dating

Samples were collected from upper plate of Mindoro fault in east side Mindoro containing siliceous schist (Fig.2) and metamorphic sandstone (Fig.6), and the river sand (Fig.7, 8) were collected from the west part of Mindoro. The sample preparation follow the methods according to Liu et al. (2000, 2001). Two pieces of standard glass, NBS SRM-610 or SRM-612, calibrated against the fission-track age standard Fish Canyon Tuff (Naeser et al., 1981), were wrapped tightly and irradiated with samples. We used grain-by-grain and mica external detector techniques to obtain individual grain ages (Wagner and Van Den Haute, 1992). Zeta values (Green, 1985; Hurford and Green, 1983) for the standard glasses SRM-612 and SRM-610 were 340±12 (1σ) and 27.5 ± 1.0 (1σ), respectively. The closure temperature of zircon fission track is ca. 240 °C which is slight lower than the metamorphic temperature of the Mindoro island.

Result

Table 1, figure 3 and 9 shows the detail zircon fission track ages. The ZFT ages range from 2.3 Ma to 5.7 Ma in northeastern side of the metamorphic belt. In the northwestern side of the metamorphic belt we take the three river sand samples. Two samples shows consistent age in on the plate of Mindoro fault were about 4-5 Ma. The river sand ZFT ages in west part of Mindoro were quite different according to its sources (Fig.9). The river sand samples in northwestern side of metamorphic belt shows a consistent ages, ca. 4Ma.

以碳質物拉曼光譜探討台灣造山帶雪山山脈南部的變質溫度及其構造義涵

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摘 要

聚合造山帶的區域變質機制仍有許多爭議，目前主要分為兩種看法：1. 變質溫度是在聚合造山作用過程中產生(如 thrust stacking)；2.變質溫度生成於造山前的張裂到被動大陸邊緣盆地時期。台灣造山帶的雪山山脈經歷了始新世到中新世的張裂與被動大陸邊緣盆地沉積作用，並在晚中新世以來聚合成為山脈。本研究將以碳質物拉曼光譜(RSCM)分析雪山山脈中部以及南部的最高變質溫度，並輔以鋯石核飛跡年代資料，來了解其升溫與冷卻的歷史，並討論區域變質作用的加熱機制。

研究結果顯示，RSCM 變質溫度在雪山山脈中段最高，來到 480˚C 以上，向北及向南降溫到小於 300˚C；在中北段變質溫度與地層年代呈正相關，但在雪山山脈南側地利斷層以東區域，向東變質溫度增加但地層年代更年輕，或溫度分布不隨地層年齡改變。

許多區域在 RSCM 溫度約 260-300˚C 時，雖變質溫度高於鋯石核飛跡的癒合溫度(~240˚C)，但鋯石核飛跡年代僅部分癒合，且變質溫度超過 400˚C 的區域皆無明顯新生黑雲母。我們認為 RSCM 的最高變質溫度應發生於造山運動前的張裂盆地到被動大陸邊緣時期，且達到最高變質溫度後在蓬萊運動發生前降溫到低於鋯石核飛跡封存溫度，以致鋯石核飛跡年代為部分癒合。

此外雪山山脈南段 RSCM 變質溫度與地層並無明顯關係，我們認為這反映張裂盆地時期，相同時代地層的沉降速率不同，盆地中心有較厚的沉積，造成較年輕地層在盆地中心因沉積厚度較厚反而有較高變質溫度。

地利斷層在水里坑斷層以南上下盤分別為始新世與中新世地層，溫度差約 80–135˚C，顯示 RSCM 變質溫度可以反映斷層作用。

應用分布式光纖感測技術分析近地表特性：以臺中中部濱海地區為例

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摘　要

近期發展的分佈式光纖聲學感測(Distributed Acoustic Sensing, DAS)技術，在工程應用、石油勘探、地質碳封存監測與地震學研究領域引起了廣泛的關注，相較於傳統地震儀，DAS憑藉其密集的空間取樣能力，不僅可以獲得高解析度的資料，還能方便地部署在複雜的感測環境中，這些特點使DAS在城市和工業區的近地表特徵分析上展現出廣泛的應用潛力。

本研究使用臺中中部濱海地區1000公尺長的交通噪聲震動訊號，並進行訊號特徵及其在地質探測上的應用研究。我們運用地震干涉法從24小時的交通噪聲中重建了表面波訊號，從而提取頻散曲線，並利用這些資料反演得到測線下方的二維剪力波速度剖面，該剖面長達800 m，深度達100 m，其中Vs30的值約為223 m/s，根據NEHRP分類，土壤分類為D級；二維影像結果顯示，該測線下方是均勻的沉積構造，沒有明顯的側向構造，縱向速度隨深度增加而遞增，且在深度40 m處有明顯的界限，這與地質資料相互吻合: 40m深以上主要為粉質砂土，以下則為灰色黏土特性。本研究的結果有效證明了利用基於DAS技術的交通噪聲進行近地表特徵分析的可行性和有效性。

火箭爆炸引發電離層電漿擾動研究

Ionospheric disturbance induced by rocket explosions launched in 2023.

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摘 要

電離層擾動會對地面的通訊、定位等產生影響。從以前的研究中可以發現，不論是對流層中規模較大的天氣現象，抑或是大地震與火山活動，都有機會對電離層產生擾動。人為活動同樣會造成電離層擾動，近年來許多國家發展太空任務，科學家發現當火箭發射通過電離層時，會在電離層中產生同心圓向外擴散以及V字型電漿擾動痕跡。本研究針對火箭發射失敗爆炸所產生的波動，是否對電離層造成擾動進行研究，以及分析擾動形態與產生何種波動影響。本次研究的事件為SpaceX於2023年發射兩顆重型火箭，皆以失敗收場。兩次發射到爆炸時長分別為4分鐘和11分鐘，飛行高度約為30公里和150公里，最後結果皆在空中爆炸損毀。

研究主要針對火箭在空中爆炸所導致的波動是否對電離層產生擾動。研究數據使用美國地面測站接收GPS/GLONASS衛星訊號計算電離層全電子含量TEC，並進行小波分析Wavelet analysis以及帶通濾波器Bandpass filter，找出影響電離層的訊號頻率/週期，並計算出擾動波的傳遞速率。

關鍵字:電離層擾動、全電子含量、小波分析、帶通濾波器

Abstract

Ionospheric disturbances have impacts on ground communications and positionings. According to the previous research, large-scale weather phenomena in the troposphere, earthquakes, or even volcanic activities, have the potential to disturb the plasma density in the ionosphere. Human activities also contribute to ionospheric disturbances. In recent years, with the development of space missions by many countries, scientists have found that when rockets are launched through the ionosphere, they will create the concentric circle outward plasma disturbances and the V-shaped plasma disturbances in the ionosphere. In this study, we are focus on the ionospheric total electron content (TEC) disturbance that caused by rocket launch failures and explosions, and further analyze the types of disturbances and their effects. The events chosen in this research are two heavy rocket launches by SpaceX in 2023, both of which ended in failure. The duration from launch to explosion was 4 minutes and 11 minutes respectively, with flight altitudes of approximately 30 km and 150 km. Ultimately, both launches destroy in midair.

The study primarily focuses on whether the plasma disturbances caused by rocket explosions in the ionosphere. The signals from ground-based GNSS networks in United States are employed to calculate the TEC of the ionosphere. Using the methods of wavelet analysis and the bandpass filter, this study finds the specific frequencies/periods that affect the ionosphere and further calculate the propagation velocity of the disturbance waves.

Key words: ionospheric disturbance, total electron content, wavelet analysis, bandpass filter

Pre-earthquake Ionospheric Disturbances in Total Electron Contents Appear before the 18 September 2022 M6.8 Taitung Earthquake

2022年9月18日規模6.8台東地震前電離層全電子含量擾亂

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Abstract

On 18 September 2022, at 10:44 LT (UT+8 hours), an earthquake with a depth of 42.7 km and a magnitude of M6.8 occurred in Taitung (23.14°N, 121.20°E). Global Ionospheric Maps (GIMs) are used to examine disturbances of the total electron content (TEC) appearing prior to the earthquake. Results show that GIM TEC specifically over the epicenter increase significantly on 22 and 30 August 2022, which are 27 and 19 days before the earthquake. TECs derived by local ground-based GNSS (global navigation satellite system) receivers in Taiwan are employed to study the pre-earthquake ionospheric disturbances (PEIDs) in detail. The ion density and ion velocity measured by AIP (advanced ionospheric probe) onboard FORMOSAT-5 are examined to find causal mechanisms of the PEIDs.

Attention-based Neural Network for On-site Earthquake Early Warning

基於注意力機制之神經網路運用於現地型地震預警

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To improve the on-site earthquake early warning of PGV, we employ the power of machine learning as leverage. A new attention-based (transformer) architecture has been proposed to solve this challenging problem. A series of comparisons with other methods are conducted, including the traditional peak P-wave displacement amplitude, and the long short-term memory neural networks. In addition to the above, we also demonstrate that the effect of building can be alleviated by including station correction of the peak values in the seismograms.

Improving Vertical Referencing of Multi-Temporal DEMs through Spectral Analysis to Measure Topographic Changes Due to Extreme Events: A Case Study from Zhoukou River Basin, Southern Taiwan

透過光譜分析改善多時期 DEM 的高度較準以量測極端事件引起的地形變化：以南台灣濁口溪流域為例

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The topography changes rapidly in places like Taiwan, which witness frequent extreme events such as heavy rainfall brought by typhoons. These events trigger large landslides, slope failures, and mass wastage, dramatically altering the local terrain. DEMs (Digital elevation Models) acquired before and after these extreme events can monitor the immediate effect of this event on topography. Quantifying changes caused by these events is crucial for hazard management. However, due to the lower magnitude of desired signals and more noise associated with the open-sourced DEMs, as well as the complexities of vertically referencing multi-temporal DEMs acquired from various sources and techniques, including datum inconsistency and other factors, such studies are limited in accurately quantifying Earth's topographical changes using moderate-resolution data.

To address this limitation, we introduce a novel approach for vertically coregistering multi-temporal moderate-resolution DEMs, offering a means to monitor changes in Earth's topography effectively. We use the Fourier transformation and spectral analysis of the DEM to identify the low-frequency components of DEMs or long-wavelength topography, which remains unchanged for a few decades. With the help of these long-wavelength topographical components, we perform vertical coregistration of the DEMs. We applied our method at a test site in the Zhoukou River basin in southern Taiwan to assess topographical changes induced by extreme events, yielding discernible erosional and depositional signals with promising results. Our findings demonstrate that, through an improved method for vertical coregistration, we can utilize multi-temporal DEMs to analyze the topographical changes on the Earth's surface resulting from extreme events.

Core CT Scanning Innovations: Bridging Practical Insights and Analytical Advances in Digital Core Physics

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Under the goal of achieving net-zero carbon emissions by 2050, comprehensive subsurface analysis is imperative for initiatives like carbon capture and storage (CCS), geothermal development, and geological hazard assessment. At the National Taiwan University, our high-resolution X-ray Computed Tomography (RXCT) laboratory plays a pivotal role in these endeavors, offering detailed insights into core samples' structural and compositional attributes through non-destructive digital core physics (DCP) techniques. Employing RXCT, our lab has advanced the understanding of geological processes and properties critical for both CCS and geohazard analysis. Key projects include multi-scale porosity evaluation of reservoir sandstones, which is essential for optimizing CCS strategies by accurately assessing storage capacities through advanced image segmentation techniques. This work not only refines porosity and permeability measurements but also enhances the resolution and accuracy of subsurface models, guiding effective CCS implementation. In parallel, our research extends to analyzing lithofacies and turbidity currents, which are crucial for reconstructing depositional environments and understanding sediment transport mechanisms. By integrating X-Ray CT with X-Ray Fluorescence (XRF) scanning, we have achieved a nuanced analysis of sedimentary structures and chemical compositions, offering new perspectives on geological hazards and sedimentary processes. Our laboratory's endeavors in noise reduction techniques further underscore the significance of DCP in geoscience research, yielding clearer, more accurate images that facilitate detailed property analysis. This holistic approach not only aids in the precise evaluation of geological reservoirs for CCS but also enhances the understanding of geohazard dynamics, contributing to safer and more effective environmental management.

Keywords:
Digital Core Physics, CCS, geohazard, porosity, lithofacies, noise reduction

氣候變遷下高屏溪與曾文溪流域之水文特徵模型建立與收支特性初探

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摘　要

在氣候變遷下，不僅對於地球系統內的水體流動產生劇烈變化，並對水文遷移與收支平衡產生了重大影響，進而牽動整個地球環境變遷及時空演化。為深入研究氣候變遷對水文系統演化趨勢和機制的影響，建立涵蓋從山區到海岸的全流域範圍完整且長期的水文觀測網，將有其必要性。本研究擇定南台灣降雨時空分布不均的高屏溪與曾文溪為研究流域，建構山區至海岸的大氣、地表水與地下水水文監測網，補足過往缺乏的「上游山區」及「下游海岸」觀測資訊，並以「長期」與「高密度」的水文特徵觀測為基礎，搭配「多重」現地試驗進行研析。本研究透過直接觀測山區降雨量、河川輸砂量、地下水位，以及量測蒸發散量、土壤含水量、河川出滲與入滲，同時分析水質與同位素組成，進行地表和地下水的流動特性分析，探討山區河川和地下水的水源及流動路徑、評估地下水的山前(mountain front)與山體(mountain block)的補注情況。海岸地下水系統則針對海岸地下水流場、海水入侵範圍、淡海水面交互作用及其控制機制進行探討，藉此建構海岸地下含水層水文特徵模型。初步分析成果顯示，既有水文測站資料呈現山區水文收支不平衡，蒸發散量的變異影響後續氣候變遷影響之評估與調適策略之擬定。夏季山區地表水的主要補注來源為降雨，而人工結構物和河道幾何形狀導致了河川斷流現象，進一步導致了河川生態和農業水資源之間的競合，而河川下游復流河段以淺層地下水的補注為主，凸顯淺層地下水路徑與量體對於下游河川流量扮演關鍵的控制；透過海岸地區地下水觀測井量測與試驗，可判釋淡、海水交界面與地下水鹽化之範圍。未來將持續研析各項水文特徵以建構完整的山區及海岸水文特徵模型及水文收支，嘗試建立山區耦合氣象-地表水-地下水之水文地質特徵模型，期望提供後續氣候變遷緊急狀態下之調適策略擬定的科學依據。

關鍵詞：觀測網、山區水文、海岸水文地質、水文收支、氣候變遷、台灣南部

判斷高雄茗濃溪之山前補注及山體補注

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摘要

在氣候變遷下，受到降雨時空分佈改變的影響，將導致地下水的補注受到衝擊。山區潛藏著豐富的地下水資源，亦為地下水補注的源頭，瞭解山區地下水如何流向下游平原區進行補注，將有助於提升地下水資源管理與運用之成效。山區地下水補注下游平原區的機制可區分為山前補注（mountain front recharge, MFR）與山體補注（mountain block recharge, MBR）兩種形式，不同的補注機制代表著不同的水流路徑、地下水年齡及化學特徵，如何區分兩種不同的補注機制，是許多專家學者研究的重點之一。本研究選定屏東的茗濃溪進行試驗，於新威地區及寶來地區的兩口地下水觀測井進行試驗。以分散式光纖溫度感測器（fiber-optic distributed temperature sensor, FO-DTS）為基礎，透過主動式加熱試驗（active-DTS, ADTS）獲取不同深度的溫度變化資料，並利用ATDS-toolbox 解析地層的透水區段，同時量化推估地下水流速。試驗結果顯示，在新威地區，井下 20-40 公尺及 120 公尺以下有較高的流速，然而 30-40 公尺的井下背景溫度與 40 公尺以下有著顯著的差異，推測有可能與不同的補注源有關；在寶來地區，因受到剪裂的影響，井下 60-72 公尺之間有較快的流速。綜合所有資料顯示，茗濃溪沿岸可能同時存在 MFR 與 MBR，為一種混合補注的形式。未來將持續在茗濃溪沿岸的地下水觀測井持續進行加熱試驗，並同時搭配抽水試驗、地電阻影像剖面法（electrical resistivity tomography, ERT）來獲取更近一步的水文特徵，確認此區域內的地下水補注行為，提供日後地下水資源評估之重要參考依據。

關鍵字: 高山水文地質、山前補注、山體補注、主動式加熱試驗、茗濃溪

隘寮溪農業取水口河段河道伏流水量推估

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摘　要

本研究以三地門鄉與瑪家鄉地區之隘寮溪河段作為研究區域，隘寮溪為山地進入平原之蜿蜒河段，其水文條件受河川形狀及山區邊坡補注影響。此外，此河段為高屏溪上游支流，河段上亦有農田水利署設置之隘寮堰，因此研究區域內出現河川水流與農業灌溉取水設施間之競合關係，使枯水期時(乾季)研究區域內有斷流以及復流現象發生。

本研究透過現地實驗，以地電阻探測 (ERT) 搭配示蹤劑實驗，分析河床底下地層剖面之電阻率變化特性，推估斷流河流下方之伏流水潛在路徑以及流速。本研究於2022年十月共六條測線發現隘寮溪河床下特定深度下有較低之電阻率，暗示河道下該深度有含水層存在之可能，可能為伏流水或地下水之流動區域。在2023年四月(乾季)、十一月(乾季)及十二月(乾季)時於上游河道上投放鹽水示蹤劑後，發現下游斷面之特定位置電阻率下降，並Time-lapse方法監測地層剖面電阻率變化，推估隘寮溪河床底下之伏流水流速約為4.63 - 5.75×10^{-4} (m/s)。而研究結果顯示，即使河床乾涸，河水仍以伏流水形式流至下游進而形成復流區段。鹽水示蹤劑流動路徑受沉積物粒徑以及非飽和層影響，其流動路徑集中於含水層之特定位置。期望本研究結果能夠提供相關數據，協助地方河川生態、農業與整體高屏溪水資源管理單位，透過工程與非工程手段共同度過氣候變遷下的水資源管理挑戰。

關鍵字：示蹤劑試驗,伏流水, 地電阻

Estimate the groundwater flow rate in the hyporheic zone in Ailiao River

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Abstract

This study focuses on the section of the Ailiao River in Sandimen Township and Majia Township as the research area. The Ailiao River is a meandering section where mountainous terrain transitions into plains, and its hydrological conditions are influenced by the shape of the river and the recharge of side slopes. Additionally, this section of the river is an upstream tributary of the Gaoping River, and there is also the Ailiao Weir built by the Taiwan Irrigation Agency in the area. Therefore, there is a conflict between river flow and agricultural irrigation facilities in the research area, leading to cut-off flow and reflow during the dry season.

This study deployed in-situ experiments, combining electrical resistivity tomography (ERT) with tracer experiments, to analyze the variations in electrical resistivity profiles of subsurface layers under the riverbed. This approach aimed to estimate the potential pathways and flow rates of hyporheic flow beneath the cut-off section. In October 2022, six ERT lines revealed lower resistivity at specific depths under the Ailiao River, indicating the possible presence of aquifers or subsurface flow zones at that depth. In April, November, and December 2023 (dry seasons), salt tracer experiments in the upstream channel resulted in decreased resistivity at specific locations in downstream cross-sections. Using time-lapse monitoring of resistivity changes, the hyporheic flow velocity beneath the Ailiao River was estimated to be approximately 4.63-5.75×10^{-4} (m/s). The study findings indicate that even when the riverbed is dry, hyporheic flow continues downstream, leading to reflow segments. The flow path of the salt tracer is influenced by sediment grain size and unsaturated layers, concentrating in specific locations of the aquifer. These results are expected to provide valuable data for local river ecology, agriculture, and overall water resource management of the Gaoping River, assisting in managing water resources under climate change challenges through both engineering and non-engineering principles.

Keywords: electrical resistivity tomography (ERT), tracer experiment, hyporheic flow

以熱與鹽水示蹤劑解析屏東三地門井場淺層地下水流特性

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摘要

面對全球氣候變遷及極端氣候，了解水文循環與水文收支平衡有其必要性。山區的地下水對被認為是下游的重要水源供給之一，然而，由於地處偏遠，基礎資料缺乏，對於山區地下水的流路尚未有一完全的解析。為近一步瞭解地下水流路及量化分析其相關水力特性，示踪劑試驗為一種常用的現地量測方式。本研究於屏東三地門隘寮溪流域之河川曲流井場，選定其中兩口淺井進行熱與鹽水的示蹤劑試驗，嘗試解析淺層地下水流流場，並探討其與地表水間交互作用關係。三地門井場之淺井均有安裝光纖進行溫度量測，並配有水位計進行水位、水溫及導電度之觀測。試驗以跨孔的熱與鹽水示蹤劑進行，並於示蹤劑試驗進行時，利用時序地電阻影像剖面法（time lapse electrical resistivity tomography, time lapse ERT）及分散式光纖溫度感測器(Distributed Temperature Sensor)進行監測，期能完整描繪地下水在三維空間中的流動行為。初步結果顯示；跨孔的鹽水示蹤劑搭配 time lapse ERT 試驗顯示地下水流呈現東北往西南的流向，主要在地表下 8 至 12 公尺處流動。依據鹽水的抵達時間，淺層含水層的水力傳導係為 4.648×10^{-3} m/s；然而，在跨孔的熱水示蹤劑中，觀測井的井外光纖並未接受到顯著的熱水訊號，井內設置的水位計則有接收到熱水訊號，分析結果可獲得與鹽水示蹤劑相近的水力傳導係數。後續的研究工作將持續進行不同流場條件下的示蹤劑試驗及不同深度的單井光纖加熱試驗，並進一步結合地表地球物理探測，期能完整地描繪三地門井場之地下水流流場及解析該場域之水文地質特性。

關鍵字: 山區地下水、地下水流場，示踪劑試驗，分散式光纖溫度感測器，時序地電阻影像剖面探測法

應用端源混合分析法了解高屏溪之水源及其交互作用

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摘　要

臺灣高山型溪流之水源及其交互作用仍未被充分瞭解。本研究以高屏溪為研究對象，利用端源混合分析法（End Member Mixing Analysis, EMMA），試圖瞭解高屏溪水源及其交互作用情形。本研究於高屏溪流域設置26個水質測站進行月尺度的採樣，並以15種地球化學參數作為示蹤劑，根據EMMA的成果，發現荖濃溪水質變化導因於三個地表水端源混合之結果；隘寮溪流至沖積層直至出海口前，水質隨時間呈現高變異，顯示為上游河水與一個未知端源之混合結果，流量越小則未知端源的貢獻百分比越高；此外，三地門河水與三地門13公尺深的井水呈現相似的訊號，暗示地表水與地下水有交互作用現象。本研究之成果有助於釐清高屏溪水源及交互作用之情形，將有助於瞭解氣候變遷導致降雨時空分布不均下之河川響應提供水文科學基礎。

關鍵字:伏流水、端源混合分析法、地表水與地下水交互作用

Application of end-member mixing analysis method to identify the water sources and interactions of Gaoping River

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Abstract

The water sources and interactions of small mountainous rivers in Taiwan are not yet fully understood. This study focuses on the Gaoping River and uses the end-member mixing analysis (EMMA) method to understand those water sources and interactions. Twenty-six water sampling sites were set up in the Gaoping River watershed for monthly sampling, using 15 geochemical parameters as tracers. According to the results of EMMA, the variations in the water quality of the Laonong Stream are attributed to the mixing of three surface water end-members. From the Ailiao Stream to the alluvial fan and before reaching the estuary, the water quality shows high variation over time, indicating a mixture of upstream stream water and an unknown end-member. The contribution percentage of the unknown end-member increases as the flow decreases. Furthermore, the stream water from the Sandimen shows similar signals to the water from a nearby 13-meter deep well, implying interactions between surface water and groundwater. The results of this study help clarify the water sources and interactions of the Gaoping River, providing a hydrological basis for understanding river responses to uneven rainfall spatiotemporal distributions caused by climate change.

Key words: hyporheic water, end-member mixing analysis, surface water-groundwater interaction

一件臺灣真露脊鯨屬鼓泡化石的形態描述及初步分類

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摘要

臺灣四面環海，鯨豚的目擊紀錄相當豐富，亦有許多鯨豚化石出土的紀錄。主要包括短肢領航鯨、海豚屬、臺灣鯨、露脊鯨科及灰鯨科的化石。然而過去研究僅仰賴單一標本之形態特徵，缺乏完整的比較。本研究報導一件來自更新世澎湖水道耳骨化石紀錄，雖然突起(sigmoid process)部分斷裂，但整體能為一塊保存完整的右邊鼓泡(tympanic bulla)化石。

本研究藉由比對現生鬚鯨耳骨特徵以及親緣分析，發現本件標本的形態特徵最接近現生的真露脊鯨屬(*Eubalaena* sp.)，其判斷依據為：鼓泡腹面有一條凹陷的溝(dorsoventral compression)、主脊(main ridge)與苞脊(involucral ridge)在鼓泡前端重疊及苞脊沒有延伸至鼓泡後端。然而，目前現生臺灣周邊海域並無真露脊鯨屬的物種目擊紀錄，而已知的現生真露脊鯨屬包括南露脊鯨(*Eubalaena australis*)、北大西洋露脊鯨(*Eubalaena glacialis*)及北太平洋露脊鯨(*Eubalaena japonica*)，皆

分布於高緯度海域，僅於繁殖季時會遷移到緯度較低的海域生殖育幼，其中，北太平洋露脊鯨的分布範圍距離臺灣海域較近，我們推測過去真露脊鯨屬的棲息地可能延伸至臺灣海域；或是現生真露脊鯨屬的族群分布有覆蓋到臺灣海域，因為族群個體數太少而未有目擊紀錄。

關鍵字：

鯨豚、更新世、澎湖水道、形態學

臺灣首件內含節肢動物之化石樹脂初探

A Preliminary Study of the First Arthropod-Included Fossil Resin from Taiwan

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摘　要

琥珀是一種古代植物樹脂化石，樹脂被分泌出後經第一階段聚合反應，再經過第二階段揮發物逸散後硬化變質即有機會成為琥珀。過去曾報導琥珀分布年代從石炭紀至新近紀皆有，然臺灣地質年代較為年輕，除 2023 年發表之利吉琥珀外，少有化石樹脂發現記錄。而利吉琥珀源於混同層，可能來自外來板塊搬運物質而不完全屬於產自臺灣原地層之琥珀。事實上，2010 年黃能偉與顏一勤曾於臺灣地層研討會報導一件臺南東山糖恩山層採集之化石樹脂標本。該樹脂內含節肢動物化石，為臺灣首件內含生物之化石樹脂。但當時僅有該生物的簡單描述，未有進一步的詳細分析。

鑒於化石樹脂究竟為琥珀或柯巴(copal)並不易使用肉眼分辨，本研究利用拉曼光譜(Raman spectroscopy)及傅立葉轉換紅外光譜(Fourier-transform infrared spectroscopy, FTIR)檢測此化石樹脂標本，紅外光譜結果顯示其具有環外甲烯(exocyclic methylene)之 1642、887 cm^{-1} 特徵峰但強度較低，因此該結果指示此標本可能屬於琥珀。另為了解該化石樹脂化學性質，本研究進一步利用熱裂解氣相層析質譜法(Py-GC/MS)進行分析，推測化石樹脂組成成分及可能樹種。本研究也利用國立自然科學博物館之電腦斷層掃描(computed tomography, CT)系統，推測此化石樹脂內含節肢動物化石可能為蛛形綱(Arachnida)的物種。

關鍵字：
糖恩山砂岩、琥珀、蛛形綱、傅立葉轉換紅外光譜、熱裂解氣相層析質譜
Tangenshan Sandstone、amber、Arachnida、Fourier-transform infrared spectroscopy、Py-GC/MS

何去何從？沙錢（棘皮動物門；海膽綱）的演化分類位置現況

Polytomy: On the new taxonomic positions of sand dollars (Echinodermata; Echinoidea)

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Keywords: Clypeasteroida, Scutelliformes, Astriclypeoidea, Mellitoidea, Taiwanasteroidea

Traditionally, Laganiformes, Scutelliformes, and Clypeasterina form a monophyletic clade Clypeasteroida based on morphologic characters. On the other hand, the new clade Luminacea that include the fourth group Cassiduloida is proposed due to the advance of genomic sequencing. Unlike the previous clades that were defined based on synapormorphies of morphologic characters, Luminacea is based purely on molecular evidence and is currently not supported by any known morphologic traits. Recently, my colleagues and I tested the hypothesis by adding new data from Taiwan and adjacent countries and increasing ingroup taxa sampling from 13 to 25 taxa. Results showed slightly different relationships among these four clades than the original relationships proposed for Luminacea. Due to the weak support in the deep nodes, polytomies among the four clades are the best solution at the moment. The monophyly of the Scutelliformes, including Astriclypeoidea, Mellitoidea, and Taiwanasteroidea, is still valid. The exact taxonomic position of Laganidae is still uncertain based on available molecular evidence.

地礦中心項目成果：苗栗更新統鈣質超微化石生物地層帶再研究

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更新統超微化石帶包括 NN16、NN17、NN18、NN19、NN20 和 NN21。其中，NN19 可再細分為 NN19s、NN19a、NN19b、NN19c 等 4 個亞帶。NN19s 以 *Discoaster brouwreri* 之頂界至 *Gephyrocapsa* (≧4um)（即中型 *Gephyrocapsa ocenica*）底界之間為定義，可對應至 Backman CNPL7 化石帶，年代相當於 1.95Ma - 1.70Ma。NN19a 亞帶以 *Gephyrocapsa* (≧4um)底界至 large *Gephyrocapsa* (≧5.5um)頂界或中型 *Gephyrocapsa ocenica* 首次消失面為定義，可對應至 Backman CNPL8 化石帶，年代相當於 1.70Ma - 1.23Ma，此亞帶又可依 large *Gephyrocapsa* (≧5.5um)之底界（年代 1.57Ma）為界線，分為上下兩部分，上部年代 1.57Ma - 1.23Ma，下部年代 1.70Ma - 1.57Ma。NN19b 亞帶以中型 *Gephyrocapsa ocenica* 消失區段為定義，此亞帶內個體小於 4um 的 small *Gephyrocapsa* 明顯增多，一般亦稱此亞帶為 small *Gephyrocapsa* 豐帶，可對應至 Backman CNPL9 化石帶，年代為 1.23Ma - 1.02Ma。另外，此亞帶又可依 *Reticulofenestra asanoi* 底界（年代 1.11Ma）分上下部，上部年代 1.11Ma - 1.02Ma，下部年代 1.23Ma - 1.11Ma。NN19c 亞帶以 *Gephyrocapsa* (≧4um) 消失區段頂界至 *Pseudoemiliania lacunosa* 頂界為定義，此亞帶內再度出現的中型 *Gephyrocapsa ocenica* 以日字型為主，其和 *Pseudoemiliania lacunosa* 兩者共存為最重要特徵，可對比至 Backman CNPL10 化石帶，年代相當於 1.02Ma - 0.43Ma，另外，此亞帶又可依 *Reticulofenestra asanoi* 頂界（年代 0.89Ma）分為上下兩部分，因此若 *Reticulofenestra asanoi* 在此亞帶內出現，可據此判釋為屬 NN19c 亞帶之下部。

在臺灣北部麓山帶優良地層剖面計畫執行期間將更新世地層岩樣作超微化石分析，結果穫得位在不同剖面的海相化石密集層得以有更精細對比和年代制約。本研究整理了有關更新統鈣質超微化石生物地層帶、指準化石生物地層面及其年代資料，對苗栗西部麓山帶重要化石富集層產地提供超微化石帶年代資料。

關鍵詞：地層與古生物；鈣質超微化石；西部麓山帶；過港貝化石層；龍王峽谷；後龍溪

Searching for Needles in a Haystack: A Preliminary Study for Echinoid Spines Preserved in Marble

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Keywords: Taroko National Park; Tananao Complex; Shakadang River; Central Cross-Island Highway; Echinodermata

The main sources of lime in Taiwan are limestone and marble, with the latter accounting for over 99% of the total reserve. Previous study on stable isotopes indicates that the original sedimentary environment of marble was primarily the reefs along the marine continental shelf. Although the protolith of marble is marine limestone with calcite as the main mineral component, the strong metamorphic influence results in observable changes such as granular recrystallization, segregation banding, ductile folding, stylolitic foliations and mylonitic structures. When limestone, originally rich in fossils, undergoes such high degree(s) of metamorphism, it leads to deformation and recrystallization, making fossil identification challenging.

Based on previous reports of preserved echinoderms in the Tananao Complex, one fossil-bearing thin section was re-examined for the distinctive stereomic microstructures. Additionally, a research permit issued by the Taroko National Park was obtained to collect marble samples along the Central Cross-Island Highway, searching for more fossil evidence preserved in thin sections.

精確估算現生鳥類骨細胞的形態與體積以了解恐龍至鳥類的古生理演化

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摘 要

根據出土的化石和現生生物學的證據，我們知道鳥類是從中生代的恐龍演化而來的。先前的研究顯示，在恐龍演化至善於飛行的現生鳥類過程中，骨骼形態和結構的改變起了關鍵的作用。最近對於哺乳動物骨細胞的研究結果也顯示，作為骨骼機械感應器的骨細胞，能夠反映骨骼所承受的機械壓力，並且結果也顯示了骨細胞的大小和形態與脊椎動物的運動模式息息相關。此外，骨細胞的體積也被證實可用來估算物種的基因組大小、身體質量、生長速度和新陳代謝率等。

然而過去研究鳥類骨骼時，多採用二維橫斷面來觀察與測量骨組織中的骨細胞或骨細胞凹陷的結構與體積，但這種方法無法精確地估算出骨細胞的三維結構，也往往導致骨細胞型態與體積的統計結果存在極大的誤差。在本研究中，我們利用國家同步輻射研究中心 TLS 01B1 光束線的高解析穿透式 X 光顯微鏡（Transmission X-ray Microscope, TXM），來對現生鳥類的肱骨骨細胞進行精確的三維奈米斷層掃描與量測，從而建立了各種屬鳥類骨細胞的三維結構模型。分析結果顯示，相較於傳統基於兩軸等長或三軸不等長橢球體估算公式所得到的結果，傳統的二維光學影像用以估算骨細胞型態與體積的方法存在相當大的誤差。有鑒於高解析度 TXM 的拍攝資源不易獲得，在這項初步研究中我們提出了一個基於精確三維奈米電腦斷層掃描統計結果的新估算方式。透過此方法，即便其所使用的是傳統二維骨骼切面影像來進行估算，也能得到更接近真實的骨細胞形態和體積參數。透過這個新的估算方法，未來我們希望能夠進一步重建從恐龍到鳥類的古生理演化過程，這不僅有助於我們理解物種間的演化關聯，也對於解釋物種如何適應不同生態位和生活方式提供了新的詮釋。

關鍵字: 現生鳥類、恐龍、骨細胞、三維斷層掃描

Seismic potential on the northwestern Main Recent Fault (Iran) revealed by InSAR

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Abstract

The Main Recent Fault (MRF) is an important boundary fault that accommodates the oblique convergence motion between the Arabian and Eurasian plates. Several large earthquakes including the 1909 Mb 7.4, 1958-1963 three events with magnitude larger than Mw 6.0, and the 2006 Mw 6.1 earthquake had partly ruptured the central and southeast segments of MRF. However, there is no large earthquake occurred in the northwest segment in the past hundred years. In this study, the interseismic surface deformation was firstly mapped from the Synthetic Aperture Radar (SAR) images observed by the Sentinel-1 satellite. Then, the ununiformed fault slip rate, coupling ratio and locking depth are estimated based on the measured interseismic surface deformation. The results show that the interseismic fault slip rate slightly varies from ~3.7 mm/yr to ~6.1 mm/yr along the MRF. Furthermore, it is also found a gradual increasing extensional component with magnitude of 2-7 mm/yr from Morvarid to Sahneh segments of MRF. In addition, total 9 sub-segments could be divided based on the fault coupling distribution and historical earthquakes in the interest zone. A seismogenic zone is identified from the historical earthquakes, which has a good space consistency with the transition between the significant shallow locking and deep free slip zones. According to the potential seismic magnitude and estimated recurrence interval, it is found that several segments are approaching the end of their interseismic recurrence interval. Meanwhile, one segment (SF-8) may be in the early stage of a new recurrence period due to the recent several large earthquakes and a long recurrence interval.

Keywords: Interseismic InSAR deformation; fault strike-slip and extension rate; Seismogenic zone; Earthquake recurrence interval

Linking slow and fast earthquakes in Taiwan: creation and challenge

台灣快慢地震連結研究之起步與挑戰

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Close interactions between slow and ordinary (fast) earthquakes have been observed universally in the last two decades. Various slow earthquakes can happen immediately preceding large earthquakes in subduction zones. Slow slip events (SSEs) are the most massive slow earthquakes with long durations from weeks to months and years. We opened a decadal research plan in 2018 when we found a large-scale SSEs activity in the Ryukyu subduction zone in an area offshore northeastern Taiwan. Geodetic measurements indicate that an $M_w \geq 8.0$ megathrust earthquake could rupture in the shallow subduction interface and generate a disastrous tsunami. To link the slow and fast earthquakes, in the first stage of research plans, we find where the SSEs initiated in the subduction zone and their spatiotemporal slip dimensions. We observe a significant correlation between SSEs and earthquake swarms in space and time. We further observe a close interaction between SSEs and large local earthquakes, i.e., the source zone of SSEs is overlapped by the afterslip of 2002 M_w 7.1 Hualien offshore earthquake, SSE occurs in a long, locked asperity where the 1920 M_w 7.7 earthquake might have ruptured. We find a decrease in the b-value before the 2018 M_W 6.4 Hualien earthquake during the migration of foreshocks southward. This observation implies a cascading rupture process in the foreshock-mainshock evolutions. We aim to understand the mechanism of SSEs initiation and the linkage from SSEs to earthquake swarms via high-rate GNSS observations.

Key words: crustal deformation, slow slip event, earthquake swarm, stress, earthquake potential

利用 GNSS 資料分析討論台灣地震前兆所面臨的挑戰

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台灣位於菲律賓海板塊與歐亞板塊的板塊交界處，構造活躍，地殼變形快，地震頻繁。 台灣地區曾多次發生大地震。 因此，地震前兆的相關研究就顯得格外重要。 高精度全球衛星導航系統（GNSS）測量技術為研究活動構造和地球動力學甚至地震前兆提供了有效的工具。 中央氣象局等機構在台灣建立了由 500 多個站組成的密集連續 GNSS 站點陣列。 資料 GNSS 站使用 GAMIT/GLOBK 軟體進行處理。 透過消除共同誤差，GNSS 資料的精確度進一步提高，在 E、N、U 分量分別為 2.3 mm、1.7 mm 和 4.1 mm。

這些高精度 GNSS 資料將用於本研究中的地震前兆觀測。 首先，我們使用速度場變化分析、應變場分析和應變變化場分析等常規方法。 基本概念是利用固定時間間隔的前兆觀測方法。我們計算了從 GNSS 資料中獲得的速度場和應變場，利用視窗移動法估算每次移動一個月且時間跨度為一年的結果。 2021 年 4 月 18 日發生的花連-壽豐地震為雙重地震，2 次地震（5.8 級和 6.2 級；深度分別為 15 和 13.9 公里）發生時間間隔僅 3 分鐘。從常規方法我們發現，震前近場震央區速度場變化在震前 2 個多月內表現出明顯的減慢，這可能表明應變快速積累而誘發了這次地震。另一個例子是 2019 年秀林-壽豐地震，震級為 5.8 級，震源深度為 18.9 公里。地震發生前約 6 個月，應變變化顯示震央地區應變正在緩慢積累，同時也頻繁發生小震，可能為一種前兆訊號。但是，當大地震的時間間隔很短時，我們無法透過此方法觀測到前兆訊號。 例如，在 2022 年在 3 月、6 月和 9 月分別發生了 3 個 ML > 6 的災害地震，3 個事件之間的間隔非常短，因此非常難觀測前兆訊號。

其次，我們採用基線觀測法直接監測斷層活動性，以獲得大地震發生的機率。我們選擇高精度、資料完整的 GNSS 站點，將它們互連起來，形成台灣地區 80 條基線的網路。 從 2013 年瑞穗地震（ML=6.4，深度=15km）和 2016 年美濃地震（ML=6.4，深度=16.7km）來看，我們都觀察到了基線變化速率減慢的表現，可能與地震前兆相關。我們在瑞穗地區和美濃地區分別使用了 9 條和 26 條基線，其中分別觀察到 3 條和 8 條速率減慢的異常。 我們也估計了這兩次地震在不同時段的應變場，發現有應變轉移現象，意指地震發生前累積的應變會緩慢遷移到目標區域。或許可以將這兩個現象視為前兆訊號，但它們需要較長的觀測時間。基本上，這些現象要在超過 4 年以上的時間跨度基線才有可能觀測到。因此，我們要面對的現實是，當大地震頻繁發生時，是沒有間震期可用來觀測前兆現象的。尤其是 80%以上的地震都發生在台灣東部地區。大地震的震後變化影響將增加前兆監測的難度。它使所有訊號混合在一起並使台灣地區的速度場加速。此外，

有些活動斷層也會被觸發，形成一定的地殼變形改變量，或是誘發其活動。這意味著預測下一個發生較大地震的目標區將更加困難。無論如何，這項研究全面總結了我們為了實現未來地震預測而必須面對的所有前兆現象和挑戰。

GLAcier Feature Tracking testkit (GLAFT): 評估由衛星資料計算出的冰川速度地圖品質有多好

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不管是未來海平面的預測、了解冰流動力學機制，還是冰河相關災害的監測，都仰賴冰河速度的精確評估。不過，目前計算冰河速度的主流方法（衛星影像的特徵追蹤）在分析參數的選擇上非常靠經驗，計算結果更缺乏一套系統性的方法來評估品質。因此，我們提出兩個基於統計和冰河物理的數值指標，並使用加拿大育空地區 Kaskawulsh 冰河的光學衛星影像作為測試資料，使用不同的特徵追蹤流程與參數導出多張冰河速度地圖，每張地圖對應的數值指標再與 GNSS 數據互相比較。我們觀察到，指標落在推薦範圍內的速度地圖具有比較少的錯誤測量和更符合冰河物理限制的速度場，因此，這些指標非常適合用來評估計算冰河速度的流程，調整並選擇最佳的分析參數。我們目前也發表了名為 GLAcier Feature Tracking testkit (GLAFT) 的開源軟體，以利使用者計算指標與進行結果的視覺化比較。

Hydro-Mechanical Modeling of Over-Pressured Mobile Shale: Insights into Shear Dilation Effects on the Uplift at Zhong Liao Tunnel, Taiwan

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Abstract

The northern exit of Zhong Liao Tunnel on Highway 3 has experienced significant uplift since its construction in 2000. The high uplift velocity zone lies between the Chishan Fault and Chegualin Fault. Between 2000 and 2016, this region had risen by a total of 130 cm while undergoing shortening by 90 cm, a rate that cannot be solely attributed to pure tectonic movement. Drilling records within this area have revealed the presence of high excess fluid pressure layers in the Gutingkeng mudstone formation. The over-pressured mudstone might be related to the severe uplift zone according to previous studies. To model the deformation of mudstone containing over-pressured fluids, we employed a 2D hydro-visco-elasto-plastic numerical geodynamic model. Furthermore, we incorporated strain-rate- and fracture-dependent porosity into the model, which generate positive feedback between deformation and porosity increase, further enhance weakening at high strain rate areas. This effect produces larger uplift velocity and reduces the spacing between the two faults, bringing the model results in closer agreement with observed surface velocities. Our research highlights the importance of using two-phase modeling approaches to account for porous and fluid effects when simulating and predicting complex geological processes.

Keywords: Hydro-mechanical, Fluid-solid coupling, Numerical Simulation, Zhongliao tunnel, Chishan fault, Gutingkeng mudstone

Machine learning-based earthquake catalog and tomography method to analyze the characteristics of the Liuchia-Muchiliao fault zone

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Abstract

Earthquakes occur frequently in the foothills belt in western Taiwan under thin-skinned structural deformation. In the past, most of Taiwan's top ten most devastating earthquakes in the 20th century occurred in the deformation front areas of orogenic belts. Therefore, a detailed study of the seismic characteristics of the region is necessary. However, the potential for major earthquakes in this area is high. In order to prepare for effective disaster prevention in the densely populated area, this study aims to establish a dense three-component seismometer array at the front of the orogenic belt in southwestern Taiwan to enhance high-resolution imaging of fault zone structures and capture seismic wave signals. Understanding the shallow structure of faults provides important input data for modeling seismic events, helping to improve seismic risk assessment in the region. Since the deep learning neural network method has been widely used in seismic-related research, phase picking is the most critical first step in seismic data processing. Tomography method was then applied to derive a high-resolution 3D velocity structure beneath the region. The seismicity pattern shows that the Liuchia-Muchiliao fault tilts eastward and there is an obvious area of low seismicity in the study area. Tomographic analysis of the velocity structure shows the presence of significant velocity changes. It is worth noting that most earthquakes occur at the boundary between high and low velocity areas or in areas with large gradient changes in the Vp/Vs ratio. Two seismic gaps were found along the fault zone, representing areas with relatively low earthquake rates, which can serve as important indicators for assessing future seismic hazard in the area. According to the results obtained, these earthquakes nucleate at the orogenic deformation front, showing that fluid migration in formation pores can cause changes in pore pressure , thereby affecting the frictional strength of faults to rupture.

Keywords: dense seismic array, 3D tomography model, seismogenic zones, seismic hazard assessment, Liuchia-Muchiliao fault zone

Surface deformation induced by the 2016 Meinong earthquake and its implications to active folds

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Abstract

In southern Taiwan, Tainan has the high population density of 861 persons/km^2 according to the data of Department of Statistics, 2017. Important infrastructures such as Taiwan High Speed Rail and science parks also locate in Tainan. The 2016 Meinong earthquake caused damages around Tainan area.

Through detail field investigation, 230 observations of the coseismic surface cracks induced by the 2016 Meinong earthquake are presented in this study. Coseismic surface cracks trends from the north to northeast. The coseismic deformed region moved toward the W-WNW. In Guanmiao town, surface cracks were mainly distributed on both limbs of the Guanmiao syncline. The preseismic deformation was also observed along the axial trace of the Guanmiao syncline. These results give clues to high structural activities in SW Taiwan. We argue that Guanmiao syncline is an active fold with both coseismic activity and interseismic creeping, which induced nonnegligible micro-geohazards because of the continual loss. We report a new case of the normal bending-moment fault, the Luosianliao fault, which locates between the Guanmiao syncline and Chungchou anticline. However, the linkage between the shallow Luosianliao fault and the deep-seated causative fault of Guanmiao aftershocks are not known yet. We demonstrate the kinematic process of coseismic surface deformation and argue that the bending-moment fault could provide an opportunity to understand the recurrence interval of folding. The mechanism of earthquake-induced folding amplification through high fluid-pressure rocks may play a critical role in assessing earthquake hazard risks in regions with similar geology to SW Taiwan.

Coexistence of thin-and thick-skinned tectonics around the Foothills and Coastal Plain in southwestern Taiwan: insight from dense seismic network

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We employed high-resolution seismicity observed by dense seismic arrays to reveal the coexistence of foreland-verging, thin-skinned, and hinterland-verging, thick-skinned tectonics beneath the foreland basin and foothills in southwestern Taiwan. The two aseismic wedges we found likely denoted high-strength, relic en echelon horsts created in the Neogene rift stage and were separated by an NW-striking strike-slip fault. A ca. 5-km-thick, westward-dipping seismic belt appears above the aseismic wedge. Within them are antiformal stacks with vertical parallel layered seismicity. Some have been cut by either west-vergent reverse or strike-slip faults. The hinterland-dipping seismicity on the east side of the aseismic wedges suggested that less-strength rocks on its east have been ramping up the aseismic wedges from a deep-seated decollement to form a thin-skinned taper that truncates the westward-dipping seismic belt. We infer the early Cenozoic transtension resulting in en echelon half-grabens and horsts in our study area. The later plate collision made the high-strength parts of the relic horsts become aseismic triangle zones. The forelandward creeping of these triangle zones along a ductile or velocity-hardening shear zone leads to stress and earthquake concentration around them. The ongoing orogeny inverses the previous basin margin normal faults to backthrusts, and rotates the early NW-trending anti-Reidel shears clockwise to generate left-lateral faulting.

Integrated geothermal exploration of Hongchailin geothermal field in Taiwan using seismic velocity and resistivity tomography with unsupervised learning analysis

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The Hongchailin area in Ilan, Taiwan has been considered as a potential geothermal energy field in recent years. To investigate possible geothermal sources in Hongchailin, a dense seismic array comprising 186 geophones is deployed over a 5 × 4 km area covering the probable geothermal field between August 2022 and January 2023. A vibroseis experiment was operated along 4 routes across the array with 12-second sweep-frequency signals from 6 to 96 Hz. To retrieve clear vibroseis-generated P-wave arrivals, we first remove the sweep signals from the raw waveforms by the cross-correlation method, and stack the processed waveforms from successive co-site shots with the Phase-Weighted Stacking (PWS) method to improve the signal-to-noise ratio. We apply the Recursive-STA/LTA method for P-wave arrival picking. Manual adjustments and additional criteria are made for confirming and refining the accuracy of P-arrivals. Lastly, a total of 43,981 P-arrivals are collected and used for seismic tomographic inversion. There are several velocity anomaly zones in good spatial correlation with the resistivity model and the well temperature measurements, although the resolvable depth of the model is limited to ~1 km. It demonstrates the active-source seismic tomography as a valuable geothermal exploration tool. Further, we employ unsupervised learning techniques to classify and explore the resistivity-velocity relationships in each cluster. Apart from clusters associated with alluvial deposits and basement layers, there exists an anomaly zone showing positive correlations between the resistivity and velocity models. It implies varying materials such as rock composition or fluid content in this region.

瑞穗紅葉地熱地質概念模型之建構

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摘　要

本研究利用整合多領域的分析來嘗試建構瑞穗紅葉地區地熱地質概念模型，包括野外地質調查、溫泉地表熱液水化學、大地電磁、鑽井井下資料及實驗分析等。本研究為地礦中心委託資助的研究計畫，目標包括建立地下3-5公里內之地熱模型，並朝著地熱發電潛能的方向提供科學的基礎。瑞穗紅葉地熱區為中央山脈東翼的變質岩區「玉里帶」，以石英雲母片岩為主，夾雜著許多大小不一的基性岩塊。整合瑞林-紅葉地區岩石的岩性、變質構造、區域地體構造，加上井下溫度、大地電磁地下成像資料來判斷，研究區域內1-2公里深度範圍內，有四個主要的潛在儲熱層，在機制及構造上有兩種可能：1）石英雲母片岩中的裂隙密集的岩體，上覆較不透水的蓋層（可能是基性岩體片岩），含有高液壓的熱水（深循環地熱）；2）是快速掘升的高溫壓熱岩體本身所提供的高地溫梯度岩石「乾熱儲集層」（淺循環地熱）。這兩種可能的解釋，還需要再進一步的驗證，我們目前傾向於第一種解釋。淺循環的溫泉水反應了低氯離子濃度及無碳酸鹽，來源多為天水。深循環水化學反應了高氯離子濃度及富含碳酸鹽；其中碳酸鹽離子，推測來自於更西側高山地區的太魯閣帶的大理岩。而沿著紅葉溪分佈的西北-東南走向(N30W~N70W)的高角度斷層（或斷層帶），走向大致垂直於大地張應力 (東北-西南伸張)，可能是提供天水(淺部循環)以及溫泉水(淺部及深部循環)流通的重要管道。這些主要斷層帶也扮演了上湧熱液通道的角色，將地下約1-2公里深地熱儲集層的熱水帶到地表來；甚至也有可能穿透到4-5公里或更深，將深部熱源的熱水引流到1-2公里的地熱儲集層中。鑽井的資料，也顯示了地表出露的溫泉，如瑞林溫泉，可能是西北走向斷層形成上湧熱液的通道。

關子嶺地區地熱儲集層模擬與分析

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關鍵字:關子嶺溫泉、地熱發電、PetraSim、TOUGH3

摘要

關子嶺位於台南白河，為西低東高的丘陵地形，該地區有多條構造線經過，例如:枕頭山斷層、崙後斷層、凍仔腳斷層等，在地熱探勘中，斷層裂隙常是熱液遷移的重要途徑，也是在地熱發電中找到穩定熱流的關鍵；在以往的鑽探報告中，關子嶺的地下地質報告預估先前得鑽探井井底溫度可達攝氏 170 度，顯示此區域具有地熱發展之潛能。

本研究使用 TOUGH3 進行地下水流、熱交換與多相流的數值模擬，並以商業軟體 PetraSim 作為主要的可視化操作程式，TOUGH3 廣泛應用於地下水資源管理、地熱儲層評估、油氣田開發、二氧化碳封存等多個領域，這些領域皆需要深入理解地下岩層中多相流體的行為。TOUGH3 包含多個狀態方程模組，考量本計畫以模擬關子嶺-中崙區域之地熱地質模擬的目的與環境後，本計畫選用 EOS3 作為模擬之狀態方程。EOS3 主要用於模擬地下岩層中的多相流體，包括液體和氣體的同時存在之情形，適合用於地熱探勘時所面臨的情境。

地熱發電是台灣邁向 2050 淨零碳排的一個重要方向，模擬結果讓我們了解了關子嶺-中崙地區的地層溫度和熱儲集層的分佈情況，這對於未來深層地熱發電的選址有決定性的作用。本研究目的為建構一個關子嶺地區的地質與數值模型，在以地電阻探勘資料為基礎，利用地質模型資料與斷層參數做為可能的數值模擬基礎，，並運用數值模擬的方式，觀察其熱液在相關構造中的擴散方向，確認可能的地熱鑽井位置，並計算熱儲集蘊藏量，推估其發電潛能，做為未來地熱開發的參考。

由溫泉水化學探討廬山熱液與儲集層特徵

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摘　要

位於南投縣仁愛鄉的廬山溫泉區由於坐落在廬山層板岩帶且具高溫沸泉，是台灣變質泥岩區造山帶溫泉的代表。本研究採集廬山、春陽、太魯灣、菁英超過50筆水化學資料，分析其中的離子成分與氫氧同位素，試圖為廬山地熱區的熱液與儲集層提供更多資訊。

本區溫泉水主要是深層受壓含水層，並以$NaHCO_3$為主要成分。乾季時岩壁為乾熱岩形式，由裂隙冒出蒸氣或熱水，並於溪谷底部上湧溫泉水，因水脈不同、加熱後的水岩反應程度不同，氧同位素飄移程度亦不同，因而氫氧同位素值分散：$\delta^{18}O$值介於-7.3‰到-10.7‰，δD值介於-72.6‰到-57.2‰之間；濕季或暴雨後，由於河水面與地下水位上升，部分溫泉轉而以$Ca(HCO_3)_2$為主的自由地下水成分，因而溫度降低、pH值下降、總溶解固體(TDS)濃度下降，硫酸根離子濃度與鈣鎂離子濃度顯著上升，氫氧同位素值轉為集中：濕季時，$\delta^{18}O$值介於-9.2‰到-8.9‰，δD值介於-64.8‰到-58.3‰之間，並趨向天水線。乾季與濕季顯著的離子成分交替變化，是為廬山野溪溫泉之特色。而深達受壓含水層之地熱井水雖成分略有變化仍以碳酸氫鈉泉為主。

二氧化矽地質溫度計顯示：春陽地區的儲集層可能達到133℃甚至更高，馬海濮溪可達160℃以上，廬山可達170℃以上。本區溫泉部分熱液樣本偏離天水線，可能與沸騰的分液作用有關，亦可能隱含混染深層的變質水或岩漿水。而不同地區之溫泉水化學成分與氫氧同位素值無法辨識出此三地區熱液來源之差異性。

若以礦物飽和指數(Saturation indices, SI)來計算過飽合度與礦物之沉澱結垢潛勢，廬山溫泉區大多數溫泉皆處在碳酸鹽類礦物的過飽和或恰飽和狀態，溫泉井亦可見霰石結垢，野溪中則方解石和霰石並存。本區未來若進行地熱開發極需注意壓力洩降問題，方能長久經營。

以土壤熱特性推估土壤含水量之可行性研究

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摘要

在降水補注至地下水的過程中，未飽和層裡的土壤水為影響入滲的重要因素之一，獲取土壤含水量的變化對於解析水文循環將扮演至關重要的角色。目前土壤含水量的量測為時域分析法(Time Domain Reflectometry, TDR)，雖然可以非破壞性方式即時取得準確的土壤含水量資料，若是需要進行大面積的量測，則會耗費大量的人力與經費，因此找尋一創新快速、可大範圍量測方式，將為現地含水量量測帶來新的契機。本研究選用分散式光纖溫度感測器(Distributed Temperature Sensor, DTS)結合主動式加熱法(Actively Heated Fiber Optic, AHFO)進行土壤含水量的推估。首先於實驗室內進行砂箱試驗，透過控制石英砂樣本的含水量，建立適用於高、低不同含水量推估之經驗公式。爾後，為驗證經驗公式之適用性，選定位於國立台灣大學的入滲池做為試驗場址，透過反覆加熱埋設於土壤中的複合式光纖，依據溫度變化與含水量之經驗公式，推估入滲池中的含水量空間分佈。研究結果顯示，以累積溫度為基基礎之經驗公式可準確推估大部分的含水量；然而，在高含水量時，以土壤熱傳導係數為基礎的經驗公式則有較佳的結果。後續的工作將持續針對入滲池的溫度量測與含水量量測結果進行分析，精進所建立經驗公式，並評估其適用範圍，研析所提出之方法在具有異

質性土壤的可行性。寄望所提出創新的土壤含水量量測方式，在不失去準確性的前提下，可大幅降低現地大範圍量測之成本，提供空間高解析度的含水量資料。

關鍵字：土壤含水量、土壤熱傳導率、DTS、AHFO、溫度

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TDR泥沙濃度監測研發與測試

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摘　要

地球系統變遷過程中，水文變遷與收支平衡牽動整個系統的時空演化進程。針對基礎科學的觀測與研究，建構全流域集水區之水文監測網，期以因應氣候變遷緊急狀態下的調適策略。

泥沙濃度與輸砂量為基礎河川水文資訊，針對於水利工程、水資源管理，以及水土保持應用等相當重要，但如何於颱洪期間取得相關泥砂濃度資訊，實務上有其難度與限制。爰此，本研究將基於TDR泥砂濃度量測技術，以及相關現場安裝經驗，企圖整合包含流量與水質採樣相關作業需求，發展現場自記式之水文觀測系統。藉由本研究之發展，除可提升現有TDR 泥砂濃度量測技術之準確性，也同步提供相關設備與量測標準作業建議。

本計畫已於高屏溪流域設置自動化TDR SSC(河川泥沙濃度量測儀器)所需之設備，分別位於高雄旗山地景橋東側橋墩及三地門橋北側橋墩，主要設備包含固定保護感測器用鐵管、供電用太陽能板以及放置主機用儀器箱，TDR SSC主機及探測棒也已於室內完成率定並安裝於現場。

以單井 TV-DTS 進行地下水之流向與流速量測

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摘要

在地下水分析之中,首要目標是地下水流流向和流速,傳統的現地調查方式,往往需要兩個以上的複井設計來進行跨孔試驗,方可同時獲得流向與流速的資訊,傳統的方法不僅鑽井成本昂貴,同時因觀測井的分佈,導致無法接收到正確的反應訊號,進而產生推估上的誤判。為克服上述缺點,本研究以熱能為地下水流示蹤劑,以主動式分散式溫度感測器(active distributed temperature sensor, ADTS)為基礎,提出熱向量分佈式溫度感測器(thermal vector – DTS, TV-DTS)的方法,僅以單井的加熱試驗同時推估地下水流向與流速。TV-DTS 為一自製研發的裝置,主要由一條加熱光纖和四條感測光纖所組成,利用加熱光纖提供熱源,四條感測光纖所量測之溫度變化,搭配熱傳輸解析解,即可判釋出水流方向與量化水流速度。本研究於北部某地下水汙染場址進行試驗,利用兩口深度不同的井,分別進行單井的加熱試驗與 TV-DTS 測試。研究結果顯示,地下水流速約介於 0.25 - 0.34 m/day,淺層含水層(深度 8-10 公尺)的地下水流向大致呈現由東北往西南方向流動,深層含水層(深度 38-40 公尺)的地下水流向則大致呈現由北往南方向流動,與前之調查結果大致吻合。未來的工作將持續針對不同情境下之流速和流向進行分析,以確認其準確性;同時亦針對 TV-DTS 進行結構上的優化,建立一套標準化的試驗流程。本研究冀望透過 TV-DTS 的自主研發,提供水文地質調查或地下水污染場址一個高解析、低成本的調查方法,並期望未來能對於現地水文地質調查技術帶來新的契機。

關鍵字:水文地質調查、地下水流向,地下水流速,熱示蹤劑,分散式光纖溫度感測器,地下水汙染

地球物理電磁方法於水文地質應用-以八卦台地為例

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摘　要

地層的電阻率與電流在地層中流動的介質電阻率有密切關係，而地層中的水通常作為電流的主要流動路徑。地層中水的聯通性反映在地層的透水係數上。對於不同的岩性，其平均電阻率與透水係數呈正比；但對於相同的岩層，其電阻率與透水係數則呈反比。因此，通過分析地層電阻的變化，有助於瞭解地層的水文地質特性。

本研究利用聲頻大地電磁方法(AMT)針對區域內的重要構造線與主要地層進行了多條或三維分布測點探測，以建立山區與平原區邊界的水文地質架構。採用AMT 探測成果進行了四條橫向剖面的分析，涵蓋了平原區、丘陵和山區，以電阻探討地質架構。為了確認地質連貫性並探討是否存在滲水通道，除了使用二維剖面外，還採用了三維逆推計算方法，探討整個調查區域地下電阻的分布情況。探測結果顯示，八卦臺地深部的含水地層以香山段砂岩為主，其低電阻分布受八卦山背斜的影響，可以分為東翼的貓羅溪流域和西翼的濁水溪流域，屬於地下水分水嶺的特性。在三維建模中，低電阻區域主要分布在西南側的濁水溪流域、八卦臺地中南段、貓羅溪流域和八卦臺地北段。

另外，配合地質鑽探井和常流點等相關資訊，採用地電阻影像剖面法(RIP)解析了八卦臺地東西兩側深度 200 至 300 米的地下地質構造和地層含水狀況。探測結果顯示，研究區域的地層電阻率約為 30 至 2000 歐姆米，剖面地下地層依次為紅土台地堆積層、頭嵙山層火炎山段的礫石層，以及山麓地區的山麓緩斜面堆積物和沖積層。通過地層的電阻率分布和等值線的型態，可以判斷剖面地下地層和地下水的分布情況。

最後，使用多頻道電磁方法(EM)探測了八卦臺地的淺層崩積層或風化層的分布情況。崩積層厚度分布圖顯示，在八卦臺地的西北側，地勢較陡峭且有河流沖刷處的崩積層厚度較厚，約 7.8 至 9 公尺；而在沒有河流沖刷處，崩積層的厚度相對較薄，約 5.4 至 6 公尺。而在八卦臺地的東側，地勢較為平緩，崩積層的厚度最薄，約 3.6 至 4.8 公尺。由此結果可以推估，八卦臺地的西側相較於東側具有更佳的地表水流通通道。

綜合以上研究成果，可以進一步加強山區與平原區間水文地質的基本調查數據，

並作為邊界過渡帶地下水資源開發的重要參考依據。

關鍵詞：聲頻大地電磁探測、多頻道電磁探測、地電阻影像剖面探測、水文地質特性、八卦臺地

地形對火山集水區的生態水文之影響：從氫氧同位素證據

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摘 要

了解植物與河水對雨水在何種情況下有個別利用偏好，是水資源與生態系保育的堅實知識。我們調查大屯山集水區天水、植物和地熱水中的穩定水同位素。天水表現出季節循環，冬季較重的同位素，夏季較輕，特別是在南坡。北坡季風信號比南坡延遲兩週。在大屯山區，新水比例結果顯示主要是來自古老水源。在北坡集水區，河水主要來自冬季季風，而南坡則受夏季季風的影響。兩者的指標都表明，冬季植物依賴夏季降雨。河水和植物在冬季有明顯的來源，支持了生態水文分離。地熱泉水的 d-excess 有助於識別水岩相互作用，低的 d 值表示了這種相互作用。地形濕度指數顯示夏季季風對南坡河水的貢獻較高，但對植物的貢獻較低。平均線性河道方向顯著影響季風貢獻比例，東北方向的河道容易受到東北方向的冬季季風的影響。最後，我們制定了一個概念模型，說明了短時和長時尺度上的水文過程。我們的研究結果加深了我們對水文干擾對水資源和生態系統的影響的理解。

結合現地試驗及數值模式研析雲林沿海地區域之淡海水交界面

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摘　要

在全世界人口急遽增及氣候變遷下，水資源面臨嚴重短缺，人類所需要的淡水資源有很大一部分來自於地下水，尤其在人口稠密的沿海地區，對於地下水的需求更是依賴。台灣雲林沿海地區高度發展農業及工業，有過度開採地下水資源，造成沿海地區有嚴重的地下水鹽化與海水入侵問題。為有效利用與管理水資源，了解沿海地區地下含水層受海水鹽化影響並判釋淡海水交界面之位置有其迫切之需要。本研究以雲林沿海地區為研究區域，結合地下水長期監測、地電阻影像剖面法（electrical resistivity tomograph, ERT）、溫度深度（temperature-depth）剖面量測及數值模擬方式，建構雲林沿海之水文地質及海水入侵概念模型。研究結果顯示，長期的地下水位及導電度資料，宜梧地區受潛在地下水鹽化之影響。時序ERT（time-lapse ERT）更進一步顯示此區淺層含水層中有淡海水混合的情形，並受潮汐波動影響，具有約 7 小時的時間延遲。TD 剖面量測搭配數值模式 Quasi-2D，可推估地下水流速及流向。綜合所有量測資料與現地試驗結果，本研究最終建構雲林沿海地區由北至南三條剖面的海水入侵概念模型，提供地下水相關單位在後續進行地下水規劃與管理的參考依據。

關鍵詞：海水入侵、海水鹽化、淡海水交界面、地電阻影像剖面法、溫度深度剖面、雲林沿海地區

Investigation on Tectonic Characteristics and Deformation Mechanisms of Mudstone Areas in southwestern Taiwan: A Case Study of the Mudstone Region between Chegualin and Chishan Faults

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Abstract

The tectonic properties and deformation mechanisms of mudstone areas in southwestern Taiwan have been the topic of much attention. These active tectonics are mainly distributed in densely populated areas of Tainan City and Kaohsiung City, as well as industrial parks and public transportation corridors, posing significant threats to public safety and the economic development. The study area mainly covers the Pliocene to Pleistocene mudstone region between the Chegualin Fault (CGLF) and the Chishan Fault (CHSF), and both thrust faults are NE-SW trending with a strike-slip characteristic. Previous studies reported that deformation in the section from the north entrance of the Chungliao Tunnel to the Tianliao No. 3 Bridge on National Highway No. 3 may be related to the fault creeping, possibly associated with mud diapirs, development of back-thrusts from blind fault, and fold and thrust belt due to regional compression or even the properties of mudstone geomaterials, resulting in a high deformation rate that increases from CGLF to CHSF. This research would start from a microscopic perspective, using optical microscopy (OM), scanning electron microscopy (SEM), and micro computed tomography (micro-CT) to investigate microstructures of study samples. Mineral phases would be identified by X-ray diffraction (XRD); water content was analyzed via the thermogravimetric differential & thermal analyses (TG-DTA) and Fourier-transform infrared spectroscopy (FTIR). In-situ high temperature XRD and water-rock interaction experiments were performed to simulate fault frictional heating and fluid-involved reactions, exploring the changes in mineral phases and major elemental composition. This study aims to reveal the mechanism of fault creep and propose a geological model for the tectonic activity of this mudstone region.

Based on OM, SEM, and CT observations of the principal stress directions of microscopic fissure in the horizontal plane, there was other stress existed besides the principal stress vertical fault-lines, suggesting possible influences from other tectonic activities. The composition of mudstone predominantly governs the mechanical strength of fault rock-layers (e.g., the water content and the ratio of quartz and clay minerals). Deep brine is affected by CHSF tectonic activity, causing methane gas to migrate upward, and accompanied by pressure-induced formation of high-pressure fluids ascending along the fault plane. Additionally, due to the dehydration of clay minerals and infiltration of meteoric water, the brine concentration decreased at CHSF, favoring quartz dissolution and clay mineral formation, thereby reducing fault strength. Consequently, both vertical and horizontal displacements at CHSF were larger than those at the CGLF. To sum up, the deformation mechanism in this study area cannot be proposed only by a single mechanism but rather by a composite model (consisting of the regional compression, high-pressure fluid, fluid chemical reaction, and mudstone-material properties, which dominate the tectonic activity and evolve periodic behavior of fault creep in this region.

Keywords: Gutingkeng Formation, Chegualin Fault, Chishan Fault, Fault creep, Water-rock interaction, Tectonic model.

Experimental Alteration of Rock Fulgurites and Its Insights for Lightning Scars

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Abstract

Fulgurites, unique geological evidence resulting from cloud-to-ground lightning strikes, are mainly composed of a glassy matrix interspersed with mineral clasts. We have shown that the rarity of rock fulgurites is due to both production inefficiencies and rapid alteration processes. However, the alteration of rock fulgurite through time remains largely unknown. In this study, unaltered to severely altered outcropped rock fulgurites were identified on granitic gneiss to develop a reference dataset as the natural evolution of fulgurite alteration. Hydrothermal experiments on rock fulgurite (with temperatures up to 300 degrees Celsius and durations up to 117 days) were conducted to simulate rapid alteration processes. We utilized microanalytical methods including optical, transmission electron, and scanning electron microscopy, as well as Raman and optical emission spectroscopy. Results revealed that the scenarios of matrix dissolution, cavity formation, and color changes occurring on the glassy layer. Furthermore, dissolution rates derived from chemical analysis of the alteration solution were employed to estimate the alteration rate. By comparing the experimentally altered fulgurites and the estimated alteration rates with outcropped fulgurites, we illustrated the alteration evolution of rock fulgurites and established the alteration-time evolution. Our findings provide a diagnostic framework for identifying various stages of altered fulgurites in the field and facilitate the identification and characterization of lightning scars.

Elastic Anisotropic Stress-Displacement Wave Propagation Simulation Spanning Length Scales Rock Physics Model from Nano to Macro

從微觀到宏觀的各向異性應力-位移彈性波傳播模擬來探討岩石物理的研究

ABSTRACT

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Stress-wave deformation fields in anisotropic media can be approximated by Christoffel equation. Based on its solutions, phase velocity surface (eigenvalues) and polarized displacement (eigenvectors) field can be constructed by considering all possible propagation directions (wave vectors). Some interesting wave-surface topological features are predicted and described. These features include: crossover of transverse-longitudinal surfaces; mode transitions; sensitivity of flux deviations to small changes in anisotropy; shear wave speeds exceeding longitudinal waves and continuous transverse-longitudinal model conversion over a single surface. For orthorhombic symmetry (mmm), crossovers of transverse-transverse surface occur for all known cases: the transverse surfaces interconnect and form a single surface. Beyond this, some orthorhombic crystal exhibit a longitudinal-transverse crossover that causes all three surfaces to interconnect into a single surface. The unusual mode transitions are a result of the peculiar elastic anisotropy. A longitudinal-transverse mode conversion means that both longitudinal and transverse modes exist on the same wave surface. Simulation on the quasi-transverse bulk wave propagation in an off-axis unidirectional graphite/epoxy composite material under plane strain is demonstrated. Energy flux deviation and particle displacement directions and amplitude variations are included in the computations. The simulation pose an aid on understand and improve the prediction of the QT/QL waves propagation. Pure transverse and longitudinal waves along principal material axes, largest component of quasi-transverse (QT) and quasi-longitudinal (QL) waves which transverse and parallel to the directional cosine of the wave vector relative to the material axes can be recognized clearly through visualization. More realistic cases, including mineral/rock/wood or even reinforced composites can be considered in the future.

Keywords:各向異性、應力、位移、準橫向（QT）、準縱向（QL）、表面、特徵值、特徵向量、能量通量、相曲面

Keywords: Anisotropy, stress, displacement, quasi-transverse (QT), quasi-longitudinal (QL), surface, eigenvalues, eigenvectors, energy flux, phase surface

Effects of thermal conductivity on the long-term thermal evolution of the lower mantle

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Abstract

The heat flux across the core-mantle boundary (CMB) plays a key role in understanding the Earth's thermal history and evolution, as the exchange of heat between the mantle and the core significantly influences mantle convection and the core geodynamo. While traditional numerical geodynamic models have employed purely depth-dependent profiles of thermal conductivity with values typically ranging from 3 to 9 $Wm^{-1}K^{-1}$, thermal conductivity also depends on temperature and composition. Seismic tomography studies have revealed lateral heterogeneities of temperature and composition, which may leads profoundly impact the Earth's dynamics, particularly within the deep mantle. To investigate the potential impact of these variations in thermal conductivity on mantle convection, we incorporate varying thermal conductivities in a global thermochemical geodynamic model, StagYY, in a 2D spherical annulus geometry. Our aim is to provide better constraints on the geodynamic simulations of thermal evolution of both subducting slabs and primordial reservoirs and their interactions with the deep mantle.

超含水相B在高溫高壓下的熱傳導率及其對地球深部水循環的影響

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摘　要

地球表面覆蓋了大量的水，這些水可藉由板塊隱沒進入地球深部，影響了地球內部的物理及化學性質，是我們了解地球的動力學及熱演化的重要關鍵。緻密含水鎂矽酸鹽(dense hydrous magnesium silicates, DHMS)為隱沒板塊中隨著溫度與壓力變化相變而成的一系列含水礦物，可以含有水在其晶體結構中，對地球深部水循環有重要的影響。其中，超含水相B(Superhydrous Phase B)，被認為是能攜帶許多水並穩定存在於地函過渡帶至下部地函最上部的重要含水礦物，然而其性質對於隱沒板塊的影響仍有許多不了解處。

本研究將合成的超含水相B，置於高壓鑽石砧及電阻式加熱系統中模擬地球內部的高壓及高溫環境，並利用時域熱反射技術(TDTR)量測其熱傳導性質，記錄隨著溫度及壓力上升的熱導率變化，並與其他含水礦物、地函礦物進行比較。

Frictional behavior of wet illite gouges under conditions of high normal stress, high slip rates and different fluid drainages

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Abstract

Illite is the most common clay in shallow fault zones, but its frictional behavior is poorly understood due to experimental limitations. Here, using the developed sample holder, we studied how wet illite gouges behave during seismic slip. We conducted rotary shear friction experiments on water-saturated illite powders at 10 MPa normal stress and 1 m/s velocity, under both fluid undrained and drained conditions. We found that, under undrained condition, the friction coefficient (μ) initially increased to ~0.15, then weakened to a steady state value of ~0.05. Temperature measurements showed the gouge's temperature gradually rose to ~100 °C after ~3 m of slip and remained constant. In the contrast, under drained condition, μ rapidly increased up to ~0.6 with cumulative slip, and the gouge's temperature rose rapidly to 540 °C after ~3 m of slip, then dropped down to ~100 °C, and rose again to ~300 and 400 °C by the end of sliding (~4 m). Microstructural and X-ray diffraction analysis showed that, under undrained condition, the principal slip zone (PSZ) presents grain size, porosity reduction and no mineral phase change, suggesting the high pore pressure can be facilitated within the PSZ and results in fluidization. Under drained condition, the PSZ is comprised of thermally decomposed illite grains (decreasing peak of illite and bump of amorphous material generated) which is larger than the initial illite powders, as slip evolves, high frictional heat generated (vesicles were observed), suggesting high viscosity that leads to high frictional resistance. Our findings suggest that thermal pressurization is the dynamic weakening mechanism for illite gouges under undrained conditions. On the other hand, thermal decomposition is the slip-strengthening mechanism of illte gouge under drained condition. This implies that the efficient fluid pathways can cause illite-rich gouges behind the rupture front to inhibit seismic slip at shallow crustal depths.

Keywords: illite, rotary shear friction experiment, frictional behavior, thermal pressurization, thermally decomposed, fluid drainage.

應用遙測技術進行台20線勤和至復興路段邊坡安全性評估

Application of remote sensing techniques in slope instability assessment along Taiwan provincial highway No. 20 from Kinhe to Fuxing

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摘 要

近年因全球極端氣候變遷，自然災害頻率逐年提升，而臺灣在活躍的造山作用下使其地勢崎嶇、地質環境複雜，歷經地震、颱風及豪雨事件後，偶有崩塌、路基坍塌等危害發生，不僅使地貌改變，甚至影響到公共建設及道路、人民與社會之經濟損失，故此臺灣山區道路邊坡的養護成為現今重點關注工程。山區道路巡檢易受地形阻礙、植生茂密等原因，使人員在觀測時受限，為幫助維護單位可精確掌握崩塌熱區，本研究利用高精度數值地形模型(High-resolution Digital Elevation Model, DEM)進行地形計量分析，並藉由常態化差值植生指標(Normalized Difference Vegetation Index)判釋崩塌地的植生復育率、崩塌區域是否逐漸擴大，最後搭配多時序合成孔徑雷達干涉技術(Multi Temporal InSAR, MT-InSAR)，得知區域長時間之變形量且能準確定位致災區域，並達成持續觀測道路安全與防災警示之效益。

本研究以台20線勤和至復興路段為例，該路段每逢遇上颱風、豪雨或地震時，仍存在崩塌或毀損的風險，影響往來道路居民交通及民生安全。研究區域分別受民國98年莫拉克颱風及110年盧碧颱風侵害，連日降雨造成玉穗溪上游崩塌引起土石流，導致沿線下方邊坡流失、橋梁損毀等。本研究初步利用光達數值地形，比較事件前後地貌變化及探討流域集水區水文地質特性，並萃取主河道範圍，得知河道變遷的路徑。本研究藉由光學影像配合NDVI判釋，結果顯示新生崩塌形成因素為原有崩塌冠部持續活躍發育，加上局部岩屑崩滑所構成。MT-InSAR選用ALOS-2雷達衛星影像進行解算，其成果與光學影像判釋結果吻合，玉穗溪上游舊崩塌區呈現逐漸下滑趨勢，進而影響下方新生崩塌區域。

綜整台20線勤和至復興路段相關分析資料與現地調查比對後，證實易致災因子為本路段主要河道振盪及土石流堆積推擠，使主流淘刷路基，導致部分地區遭受掩埋或形成堰塞湖。本研究成果提供確切崩塌熱區及地形判釋資料，進行道路與邊坡整體安全性評估，並提供相關工程單位整治建議與參考，以增強道路安全與日後管理維護。

誌謝 本研究計畫承蒙 台灣世曦工程顧問股份有限公司「台20線勤和至復興路段水文地質長期穩定性評估及補充滾動調查服務工作及穩定廊帶安全性評估、探討服務工作」計畫案提供研究經費 謹致謝忱。

中文關鍵詞：高精度數值地形模型、常態化差值植生指標、多時序合成孔徑雷達干涉技術

Keywords: High-resolution Digital Elevation Model、Normalized Difference Vegetation Index、Multi Temporal InSAR

運用合成孔徑雷達干涉技術評估全臺大規模崩塌潛勢區活動性

Assessment of Nationwide Deep-Seated Landslide Activity in Taiwan Utilizing InSAR

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摘　要

極端氣候影響造成強降雨事件愈發頻繁，臺灣全島 1000 公尺以上的高山地區佔總面積 47%，每當颱風豪雨侵襲時常發生不同坡地災害。為防治崩塌災害帶來的潛在危害，政府相關單位積極且致力進行大規模崩塌多元監測與分析工作。農業部農村發展及水土保持署經考量致災規模、潛在風險及保全對象等因素，進一步規劃本研究 306 處廣域大規模崩塌潛勢區之活動性評估。為獲取大範圍地表變形資訊，須使用全天候、高解析度及連續空間覆蓋的合成孔徑雷達干涉技術，為現階段大規模崩塌潛勢區提供長期且定量化資訊。

本研究利用日本宇航局 2014 年發射之 ALOS-2 雷達衛星影像，配合多時域相關點雷達干涉技術(Temporarily Coherence Point InSAR, TCP-InSAR)分析廣域大規模崩塌潛勢區之地表變形資訊。同時搭配空載光達高精度數值高程模型(Digital Elevation Model, DEM)進行地形計測加值演算與分析，進一步獲得地形坡度(Slope)、地形開闊度(Openness)、地形曲率(Curvature)，以及地形粗糙度(Roughness)等圖資，有利統計、量化與影像分析大規模崩塌潛勢區之地表地形特徵。有鑑於此，多元多尺度觀測可有效掌握易致災區域，以利於後續邊坡細部規劃與工程治理之參據。針對全臺 306 處大規模崩塌潛勢區地表平均變形速率，利用地形幾何關係將雷達衛星入射視角(Line Of Sight, LOS)轉換為沿坡面滑移方向數據，而後依據活動性指標及級距門檻值進行今年度活動度分級與排序。根據分級結果顯示活動度低共 107 處(佔 35 %)，屬活動度中共 115 處(佔 38%)，屬活動度高共 84 處(佔 27%)。

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中文關鍵詞：多時序合成孔徑雷達干涉技術、高精度空載光達、大規模崩塌

Keywords: Multi Temporal InSAR, High-resolution Airborne LiDAR, Landslide

潛在大規模崩塌分類分級方法學發展及應用

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摘　要

近年每逢梅雨季或夏季時，臺灣常因颱風及豪雨伴隨許多大規模崩塌事件，如敏督利颱風、桃芝颱風、莫拉克颱風、20120610豪雨事件等，均造成諸多生命財產損失。而於莫拉克風災後，經濟部地質調查及礦業管理中心(以下稱地礦中心)雖已判釋出全臺2,500處潛在大規模崩塌，然而，目前仍缺乏適合之分類與分級標準，可進行全面性之防災策略規劃，及於山崩與地滑地質敏感區劃設實務應用或修正參考。

有鑒於此，本研究綜整日本及挪威地質調查局(NGU)之方法，針對本土化之大規模崩塌分類分級方法進行研擬。其中，日本之評估方法係參照日本地滑學會等學者發表之邊坡防災危險度(susceptibility)評估手冊，以層級分析法(Analytic Hierarchy Process Theory, AHP)為主，針對崩塌區位、發育階段與活動度高低進行評估及給定量化分數；而挪威地質調查局之方法為針對大型岩坡破壞所建立之災害與風險分級系統，並針對大型岩坡各項崩塌特徵及現地之監測資料給予不同程度之量化評分。經彙整上述兩種大規模崩塌分類分級評分法後，本研究初步建立適用於臺灣之崩塌特徵之潛在大規模崩塌分類分級level 1表，亦建立實作填表之標準作業程序，評分之高至低分為A、B、C、D四級，透過相關填表結果可初步篩選崩塌特徵較明顯之潛在大規模崩塌，並對應相關後續作為。

利用前述level 1表，本研究已完成649處潛在大規模崩塌實作填表，亦進行統計分析來瞭解潛在大規模崩塌之評分及分級情形。目前level 1表格經大量案例實作填表後，已取得合理且具一致性之成果。而為細緻化分類分級之結果，本研究目前亦已針對評分較高之A、B級，擬定level 2表格，根據其崩塌機制細分為重力邊坡變形、弧形滑動、平面滑動、巨厚崩積層等進行進一步評估，以瞭解這些潛在大規模崩塌之危害程度。

本研究後續將分年完成地礦中心所判釋之2,500處潛在大規模崩塌之分類分級，亦會針對level 2表格持續進行標準作業程序擬定及案例測試，以期能合理對A、B級潛在大規模崩塌進行更深入之危害度評估。

關鍵字：潛在大規模崩塌、分類分級、層級分析法
Keyword: potential large-scale landslides, classification and grading, analytic hierarchy process theory (AHP)

國道邊坡總體檢之回顧、發現與展望

Review, Discoveries, and Prospects of the Comprehensive Inspection of Freeway Slopes

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交通部高速公路局(以下簡稱高公局)多年來於邊坡養護作業中納入全生命週期概念，訂定巡查、監測、地錨檢測、安全評估、總體檢等作業準則，並嚴格遵守與貫徹執行，為國道邊坡之安全奠定相當深厚之基礎。

依據高公局之養護手冊規定，每隔 5 年即需辦理一次國道邊坡總體檢作業，通盤檢討養護制度與各邊坡之安全狀況，以確保其安全無虞。前次總體檢係於 108 年辦理，該次除進行養護制度成效檢視及精進外，亦增訂嚴謹之監測儀器、地錨設施退場規定，達成全生命週期永續管理之階段性目標。時光匆匆，113 年適逢 5 年一度辦理總體檢之盛事，有鑑於臺鐵猴硐、高鐵通宵、國道 1 號順向 10.1k 等事件之反思，此次總體檢與以往最大之差異，即在於利用高精度數值地形通盤檢視地質、地形特性與路權外水因子對邊坡穩定之影響，使邊坡維護管理思維不再拘限於路權內，並結合過去累積之巡查、監測、地錨檢測、安全評估等各項資料進行綜合評估，進而達到內部、外部因子兼具，治標治本之成效。

截至目前為止，高公局已完成轄區內 597 處 C 級以上邊坡之總體檢工作，除各約有 2.3%、6.2%之邊坡提升至 B、C+級以外，更於體檢過程中發現既有地質圖上未曾標示之斷層，提供國道邊坡更進一步安全評估考量之依據，確保斷層鄰近區域之用路安全。高公局將於 113 年底前完成此次總體檢工作，在與時俱進之技術推進下，除積極透過工程手段辦理補強外，亦大量增設自動化監測儀器，並擴大維護管理關注範圍，未來亦將持續審視邊坡狀況，及時採取必要措施，以保障用路人之生命財產安全。

關鍵字：國道邊坡、總體檢、高精度數值高程模型、山崩、邊坡破壞
Keywords: Freeway slopes, Comprehensive inspection, LiDAR DEM, Landslide, Slope failure

預計投稿子題：Natural Hazard
編號：NH1-山崩與土石流災害
投稿類型：口頭報告

透過土石流模型研究山區溪流的沉積物供輸變化

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摘　要

台灣位於板塊交界，地形陡峭且地質破碎，在山區容易因為降雨或地震等因素引發山崩和土石流，導致沉積物的生成與搬運。山區集水區的沉積物供應與輸送和河流作用有關，而其中較劇烈的沉積物供輸過程甚至可能引發土石流災害。好發土石流的溪流集水區中存在大量不安定的土砂，土砂來源包括坡面上的土石沖刷和崩塌產生的土石，在河流流量達到土石流啟動所需的水量後，就會產生土石流來搬運不安定土砂。

本研究主要觀察山區集水區中的沉積物供輸在極端降雨事件中的變化。南投縣愛玉子溪、出水溪和嘉縣 DF042 均為水土保持局列管中的土石流潛勢溪流，歷年來多次發生土石流。三條溪流在地質與地形因素上易在河道中和坡面上堆積土砂，當颱風來臨或鋒面停滯帶來劇烈降雨時，集水區中的逕流匯集於河道，使河流流量增加，開始搬運河道上堆積的沉積物，同時雨水沖蝕坡面上的堆積物，將更多土砂沖入河道，最終形成土石流。本研究挑選 2009 年莫拉克風災和 2012 年 0610 豪雨事件作為極端降雨事件之案例，利用 RUSLE 估算溪流坡面上的土壤沖蝕量，以及崩塌產生的土石，研究溪流在颱風期間產生的坡面產砂，並透過 RAMMS 模擬土石流發生時，不安定土砂在事件中的搬運與堆積情況，以探討在豪大雨事件期間，山區溪流集水區中的沉積物變動狀況。

藉由土石流模擬了解降雨時山區溪流沉積物的供應與輸送，可以在山區規劃坡面防護工程或野溪治理工程時作為工程設計之依據，或是後續作為河川調查、生態環境等研究之參考資料。

關鍵詞：RUSLE、RAMMS、沉積物供輸、土石流、出水溪、愛玉子溪

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Monitoring Slow-Moving Deep-Seated Landslides Using PSInSAR Techniques with an Integration of Open-Source Software: A Case Study of a Slope from the Laonong River, Southern Taiwan

利用 PSInSAR 技術與整合開源軟體監測慢滑移深層山崩：以荖濃溪新發地區山坡為例

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Abstract

Deep-seated slow-moving landslides pose significant threats to the stability of mountainous regions, affecting both human settlements and infrastructure. This study focuses on the southern part of Taiwan, specifically at the Hsinfa village in the vicinity of Laonong River, where slow-moving deep-seated landslides have been identified as a significant geohazard past 2009 Morakot Typhoon. In this study, Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) techniques, including StaMPS (Stanford Method for PSInSAR) ISCE (Interferometric Synthetic Aperture Radar Scientific Computing Environment), are employed for comprehensive monitoring and analysis. Utilization of the temporal and spatial information provided by these techniques; this study aims to characterize the movement along the slope of the identified deep-seated landslides in the Laonong River region. The integration of StaMPS with ISCE environment facilitates the identification of persistent scatterers and the detection of ground deformation associated with the slow-moving landslides. The findings of this research focused on the Sentinel 1 datasets from 2018 to 2023 contribute to a better understanding of the dynamics of slow-moving deep-seated landslides in the southern part of Taiwan. The insights gained from the PSInSAR techniques provide valuable information such as the slope is characterized by EW (Horizontal) and NS (vertical) velocity values ranging from 1.5 mm/yr to 6.5 mm/yr down the slope which corroborates with the present inclinometer stations at the site-specific areas. This observation surely helps in developing early warning systems and implementing effective mitigation strategies to reduce the impact of such geohazards on the local communities and infrastructure. Furthermore, the study highlights the significance of remote sensing technologies in monitoring and managing landslide-prone areas for sustainable development and risk reduction.

Keywords: Laonong river, PSInSAR, Deep-seated landslides, Horizontal (EW) velocity, Vertical (UD) velocity.

南沙群島海域海底擴張時期之岩漿作用與地殼構造

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摘　要

南中國海被動大陸邊緣從始新世到中新世時期歷經多期的張裂作用，在台灣、菲律賓、馬來西亞、汶萊、越南和中國等海域形成一系列的半地塹盆地。近期在大陸地殼與海洋地殼過渡帶（COT）的深洋鑽探和高品質長支距反射震測，了解拆離作用（Breakup）的速率相當快。然而在太平島周圍的西南次海盆，張裂方向從南北向漸變成西北-東南向，並且其他地球物理資料顯示，可能有較多的岩漿活動參與此地區的拆離作用，不過對於岩漿作用與海洋地殼形成的過程則尚未釐清。

本研究利用我國過去十年間在南沙群島周圍累積的地球物理探勘資料，篩選兩條測線位於南沙群島和禮樂灘之間的海域，另外兩條測線位於南沙群島西側的海域作為代表剖面。綜合多頻道反射震測、隨船重力與磁力資料分析。反射震測受波器長約1至1.5公里，並完成重合前時間移位，進行盆地尺度的地質解釋。同時將水層、沉積層和重力推估莫合面的深度輸入至地殼尺度的重力和磁力模型，利用對應的密度和磁感率參數與隨船重力異常和磁力異常觀測值比較，驗證本研究的地質解釋。

本研究的震測資料結果，能解析至中生代基盤的頂部邊界，辨識出大陸地殼區域內的半地塹盆地。在太平島東部海域，大陸地殼與海洋地殼過渡帶的區域顯示沉積層高振福反射層訊號，形成數條成層向海傾斜的反射訊號。在太平島西部海域海洋地殼的邊緣具有較厚的沉積層，往南邊大陸地殼的區域受到零星岩漿作用入侵分佈。綜合重磁力模擬顯示南沙群島和禮樂灘之間的海域有一高密度和高磁感率的地殼，初步認為地殼的密度約略為海洋地殼的密度，與震測發現的高振幅反射層位置接近。整體岩漿作用顯示散佈在南邊的被動大陸邊緣上，並在太平島東側的海域有一特別岩漿產物的震測特徵。顯示在此時期的張裂作用伴隨相對較多的岩漿作用，作為南海大陸地殼張裂歷史的重要觀察。

從海底地震儀和多頻道反射震測資料分析

澎湖盆地東側沉積層速度構造

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摘要

澎湖盆地形成於古新世晚期，為臺灣海峽中部的主要沉積盆地，且**靠近大陸邊緣之半地塹盆地構造。**澎湖盆地湖相沉積環境在始新世因張裂下沉。到漸新世早期，由於地殼運動及海退的發生而使沉積活動減少，上部與中部始新世沉積物遭侵蝕，造成最大面積的不整合面。本研究探討的**澎湖盆地東側沉積層速度構造**介於**盆地東南邊界斷層**與澎湖群島周邊**火成岩**之間。由於中國福建濱海斷層帶、**澎湖盆地東南邊界斷層**附近的活動斷層和 2018 年澎湖地震（Mw~6.21）的發生，臺灣海峽中部的斷層活動可能已經**重新激發**。為了確認澎湖盆地東側沉積構造、活動斷層和可能形成的滑移斷層花狀構造分佈，本研究分析於 2021 年 10 月在澎湖盆地東**側**由新海研二號佈放的 9 部海底地震儀和使用時差式空氣槍激發 3 條多頻道震測資料。從 2021 年收集的 6 部海底地震儀資料可觀察支距 10-20 公里的折射初達波訊號，我們選取海底地震儀資料的折射波和反射波走時，反演深度 4 公里的沉積層和上部地殼的 P 波速度-界面模型。本研究在海底地震儀震測模型深度約 1.5 公里開始發現高 P 波速度區（5-5.5 公里/秒），推測與過去**火山活動遺留構造**有關。根據澎湖盆地東側的多頻道震測剖面，除發現多處正斷層，亦可在淺層沉積層觀察到大範圍的**強反射訊號，**可能是由**噴出漫流之岩漿**形成澎湖中部次盆地和東北次盆地以東的**火山沉積構造**。另疑似**古岩漿通道**之曲狀向上訊號，與海底地震儀震測模型距離 15-25 公里及深度 1-2 公里之兩處沉積層側向速度變化對應，可幫助我們印證其為**古岩漿通道**。

關鍵詞: 斷層、半地塹、古岩漿通道、澎湖盆地、沉積層速度構造
Keywords: Fault, half-graben, old magma conduit, Penghu Basin, Sedimentary velocity structure

【口頭報告】

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由離岸-近岸震測分析新竹苗栗地區沉積層與地殼速度構造

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摘　　要

本研究區域位於西部麓山帶與苗栗新竹外海，有許多褶皺與斷層構造分佈。藉由苗栗離岸與近岸區域的地殼速度構造，可瞭解研究區域基盤到地表之間的地體構造。我們已分析2022 年 9 月由新海研一號空氣槍陣列（930 立方英吋體積）為震源，蒐集的 5 條多頻道反射震測剖面。新海研一號空氣槍的震波，也同時由佈署在新竹苗栗共 93 部地震儀接收。我們利用陸上與海上的震測資料進行首波與折射波走時反演，建立沉積層與地殼 P 波速度-界面模型。模型顯示竹苗地區的地殼構造呈現彎曲拱起的形狀，同時在近岸多頻道反射剖面觀測到受侵蝕的褶皺構造，反映竹苗地區曾因為地殼/基盤的撓曲作用，使得地殼抬升。我們也發現斷層的型態由離岸向陸地逐漸由正斷層轉為以逆斷層為主。本研究將反演後的地殼速度模型進行蒙地卡羅速度不確定性分析顯示，近岸上部地殼的 P 波速度不確定性較陸上低，且近岸上部地殼的 P 波速度約 5-7 公里/秒。基盤的 P 波速度在剖面中央達到最低速，可能代表其變質度低於鄰近同年代形成的岩體。

關鍵字：背斜、首波、多頻道震測、P 波速度-界面模型、折射震測、走時反演

Keywords: anticline, head wave, multi-channel seismic, P-wave velocity-interface model, refraction seismic, travel-time inversion

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離岸風場海域地質特性及地質安全評估

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摘　要

離岸風電是我國淨零轉型十二項關鍵戰略之「風電/光電」關鍵戰略之一，地質環境直接影響風機基礎及維運安全，為瞭解風場海域地質環境狀況，經濟部地質調查及礦業管理中心已完成彰濱(含臺中)、澎湖及苗栗外海離岸風場之調查，調查項目包括多頻道反射震測、電火花震測、底拖側掃聲納、底質剖面、多音束水深探測、岩心採樣及海床影像觀測等。預計至114年底可再完成竹苗近岸、桃園及北部風場的調查。

整合地球物理探測結果，分析可能影響風機基礎地質安全影響因子包括：淺層斷層(切穿地層淺於海面下120公尺)、沙波遷移及流體特徵(聲波反白帶或流體煙囪)，而不均勻分布的玄武岩堅硬地層(淺於海床下100公尺)可能影響基礎施工。淺部斷層主要出現在彰濱(18號、D7、D8風場及其西側)、澎湖周緣(D9、D10、D11風場)及苗栗外海(D4、D5、D6風場)。竹苗外海多活動逆斷層，並有背斜構造出露海床，地質構造較為活躍；相較彰雲砂脊北側的斷層位於較深處，活動性較低。沙波則廣泛分布於彰雲外海及澎湖群島西南側風場，其位移可能造成海床面變動而影響風機基礎埋深。聲波反白帶分布於D7風場、彰濱近岸、澎湖水道及苗栗外海，需進一步探查是否有流體存在。而澎湖周邊(16、18號及D8~D11風場)及澎湖水道廣泛分布強反射面，且離澎湖群島愈遠則愈深，可能與玄武岩的分布有關；苗栗外海也有許多強反射層分布，由於層厚僅1~2公尺且分布範圍不連續，較可能是河道沖積的礫石層。由於分布深度較淺，對風場基礎施工存有安全影響。

地質安全分級以2.5'x2.5'網格為單元，評估各地質安全影響因子特性及所占比例，將各影響風險潛勢分為高、中、低三級，並編製地質影響因子分級圖。未來風場開發商可針對高影響潛勢因子詳細調查，並可利用「離岸風電地質與環境感知系統」(網址：https://windpower.geologycloud.tw/map)協作功能規劃風場及協助決策評估，以確保風機基礎地質安全。此外，產官學界皆可依據「離岸風電地質與環境感知系統服務平臺資料提供及使用作業要點」申請地質調查資料，最大化資料使用效益。

臺灣海峽中部沉積構造和斷層構造的震測資料分析

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摘 要

從2017年開始，我們在臺灣海峽中部進行多次的多頻道反射與海底地震儀震測資料的收集，並已完成這些震測資料的分析。根據多頻道反射震測剖面，臺灣海峽的斷層分布大多是以東北-西南走向，且向西北傾斜的正斷層為主，但在彰雲沙脊西側的斷層分布則是以東南-西北走向的滑移斷層為主。推斷這些滑移斷層發生在中新世晚期(造山運動開始)菲律賓海板塊和歐亞板塊之間的碰撞期間，可能重新激發並切割到深處的沉積層。多數位於彰雲沙脊西側的多頻道反射震測剖面也發現滑移斷層特徵的花狀構造，且該滑移斷層因為靠近臺灣海峽西部的右移滑移斷層系統，推斷位於西彰雲沙脊的滑移斷層為右移滑移斷層。此外，由於彰雲沙脊前凸起抬升，造成南日島盆地前淵與前凸起邊界附近的沉積物被侵蝕，而產生沉積地層的尖滅。我們也選取海底地震儀震測資料走時、反演多條2.5公里深的P波速度模型，並疊加海底地震儀震測速度模型到多頻道反射震測深度剖面。我們發現在分離不整合面以下，P波速度可高達4.5公里/秒。在分離不整合面均顯示較高的速度垂直變化，且斷層穿過沉積層會有較大的速度垂直與側向變化。透過P波速度垂直與側向變化，可以更好的解釋多頻道反射震測剖面的斷層分布。

關鍵字:前陸盆地、右移滑移斷層、P 波速度模型、分離不整合面

Keywords: Foreland Basin, Right-Lateral Strike-Slip Fault, P-Wave Velocity Model, Break-up Unconformity (BU)

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Offshore-onshore experiment along coastal line of Taoyuan, northwestern Taiwan

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We conducted a survey consisting of 59 three-component seismic sensors to record the airgun shooting from RV Legend along three seismic lines near Taoyuan in May 2023. Data recorded from 14 land stations of high-quality data (profile length of approximate 20 km) along a NE- SW line near CPC KY-1 well was analyzed. P-wave velocity model along the offshore-onshore line near Taoyuan was built based on the stratigraphy sequence from previous studies and inverted by refracted and reflected arrivals from the land data. Distinct refracted arrivals from all sequences were identified depending on distance of seismic sensors to the sources. We found that Chinshui shale causes the abrupt change in the velocity model. Near the Taoyuan coast, a low-velocity zone of about 2.3-2.5 km/s with a height of about 1 km and a width of about 0.5 km in the Nanchuang Formation may be indicated as an old gas field near the CPC KY-1 well. Similarly, beneath the Nanchuang Formation, a relatively low-velocity intra-layer velocity contrast from 3-3.5 km/s just beneath the onshore border was also identified. This layer has a depth of ~ 0.8 km (similar to Nanchuang Formation) and its velocity decreases from north to the center of profile and increases toward south. The low-velocity zones within and beneath the Nanchuang Formation at a depth of about 1-2.8 km can be served as a potential site for the future CO_2 storage. The deepest layer has a similar velocity pattern with an obvious higher velocity (> 3.5 km/s). The P-wave velocity along these stratigraphic formations is greater offshore than onshore, probably due to a deep compaction from the flexural loading of the orogeny belt.

Keywords: land stations, P-wave velocity, refracted arrivals, stratigraphy formations, travel-time inversion

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臺灣北部近岸區斷層構造

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臺灣北部海域鄰近大台北都會區，海域斷層分布會影響都會區城市安全，山腳斷層為北部活動斷層，在陸地長度約 34 公里，以往研究可延伸至海域，其他北部陸地上的斷層如崁腳斷層及基隆斷層等，是否延伸至海域，以往也沒相關海域斷層資料可做比對。經濟部地質調查及礦業中心(簡稱地礦中心)執行「臺灣北部礦產地質調查」計畫於 2021 及 2023 年於北部近岸區收集了 1,521 公里長的震測資料(54 條測)，加上地礦中心和海洋委員會國家海洋研究院合作收集了 431 公里震測資料資料(16 條測線)，合計在北部海域收集了震測資料 70 條測線，長度達 1,952 公里。根據這些高解析的震測資料，描繪出 4 條正斷層構造，由北往南分別為外金山斷層、野柳斷層、小野柳斷層及八斗子斷層等，除了小野柳斷層未切穿海床外，其餘 3 條斷層都已切穿海床，可視為活動斷層，這些斷層都呈東北-西南走向，約略平行，顯示可能是同時期張裂應力所造成的。

外金山斷層向外海延伸長度約 29.92 公里，全線皆切穿至海床，外金山斷層為陸地山腳斷層之延伸，從近岸區精密地形資料(地礦中心另案收集的資料)，有明顯線形，外金山斷層可向陸地延伸，連接到山腳斷層，這條貫穿陸海域的活動斷層長度可達約 64 公里，對於大台北地區的安全影響不可忽視。野柳斷層位在野柳岬東側，向外海延伸約 26.95 公里，近岸切穿海床約 12.49 公里，向外海上覆沉積物未出露海床，長度約 14.36 公里。小野柳斷層未切穿海床，延伸長度約 13.62 公里，向外海地層轉變為多組小斷層發育，形成斷層破裂帶。八斗子斷層為近年來新發現的活動斷層，全程延伸長度約 28.56 公里，於近岸切穿至海床約 11.9 公里，向外海上覆沉積物未出露海床，長度約 16.66 公里，從地形對比，八斗子斷層和陸地上的基隆斷層呈線性關係，可能為相連接斷層。

整合探測資料顯示目前臺灣北部海域都為正斷層，從高解析底拖聲納資料，可發現外金山斷層及野柳斷層早期是逆衝斷層，到後期張應力影響下反轉為正斷層，亦值得我們進一步了解。

重建中國廣東沿海瀉湖的古氣候變遷

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摘 要

本研究致力於探討中國東南沿海地區在廣東的品清湖瀉湖之古環境變遷與重建。在湖域東南方岸邊取得了一根長 410 公分的沉積物岩芯，並獲得了共 12 個定年材料。透過 C-14 定年方法解釋了該地區約 8300 年前至今的環境歷史紀錄。根據 R package 的分析得知不同時期的沉積速率變化。觀察到品清湖沉積物整體沉積速率約為 0.02-0.22 cm/y，平均沉積速率為 0.05 cm/y。本研究對品清湖進行了多指標比對分析，包括沉積物粒徑、有機碳含量、碳氮比、碳同位素分析以及磁感率變化。在進入中期全新世（8200-4200 cal. BP.）時，C/N 比值達到最大值，TOC 含量與δ13C 數值逐漸攀高，並在 8000-6000 年間進入一段高度震盪時期，這段時期反應夏季季風影響最強盛的時期，而此時正是海平面上升到最高點的時期。同時，細顆粒代表因子 EM1 也在此期間出現強烈震盪訊號，與其他指標呈現正相關性，此時段的沉積速率約為 0.1 cm/y。接著在 6000-1000 cal. BP. 期間，沉積速率幾乎停止降至 0.02 cm/y，造成如此緩慢沉積的原因可能是海水面沒有繼續上升而使沉積環境逐漸穩定，或是瀉湖範圍縮小導致採樣點發生了沉積間斷。粒徑指標以及代表粗顆粒的 EM3 與 EM4 在 3300 cal. BP., 2000-1000 cal. BP.時間段皆顯示明顯的粗顆粒事件。最後，1000 cal. BP.至今，疑似是受到上游河道的出現，沉積速率攀升至最高 0.22 cm/y，其他指標在此期間也都呈現活躍的趨勢，粒徑和磁感率指標皆達到最高值。近 1000 年的紀錄以來，磁感率整體趨勢與粒徑呈現正相關，而 C/N 的高峰時期則與廣東和海南島的颱風累積數量紀錄有關。整體來說，指標的意義無法指示的精準可能受沉積環境影響有較大關係。

關鍵字: 廣東、品清湖、瀉湖、碳同位素分析、有機碳分析、粒徑分析

太魯閣峽谷是更新世氣候變遷下的生物庇護所—由花粉紀錄中的新仙女木事件說起

A Pleistocene climate-change refugium inferred from the pollen record of Younger Dryas cold event in Taroko Gorge

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摘要

新仙女木事件(Younger Dryas Event)是更新世末次冰期結束後的暖化過程中突然發生的全球性氣溫驟降事件，時間在距今 12,800 至 11,500 年前。古氣候資料顯示此次氣候驟變雖屬於全球性事件，但在高緯度地區的氣溫波動較為明顯。台灣因為緯度偏低，過去的相關研究包括南投頭社盆地(Kuo and Liew 2000; Liew *et al*. 2006; Li *et al*. 2013)和日月潭(Lu *et al*. 2009)、屏東牡丹鄉東源池(Lee *et al*. 2010; Ding *et al*. 2017)和臺北盆地五股井(曾美惠和劉平妹 1999)的紀錄中，所顯示的新仙女木變冷訊號都很微弱，不過令人意外的，花蓮太魯閣峽谷的花粉紀錄卻出現了極為清楚的新仙女木期氣候變冷的訊號。

太魯閣峽谷以獨特的地形名聞遐邇，根據鑽取自太魯閣國家公園中唯一天然湖泊蓮花池的岩心所建立的花粉化石資料(蔡育廷 2022)，在距今 12,900 至 12,100 年前期間生長在高海拔的針葉樹鐵杉屬(*Tsuga*)花粉大量出現，標示出極為明確的氣候變冷訊號，在時間上正對比於全球性的新仙女木事件。

太魯閣峽谷異常清晰的冷事件訊號值得深究。氣象觀測資料顯示峽谷內的垂直氣溫梯度在低海拔地區較大，海拔高度每上升 100 公尺氣溫將下降 0.6~0.7˚C，在中海拔 1,000 至 2,200 公尺之間則氣溫梯度較小(每上升 100 公尺氣溫下降 0.3˚C)，更高海拔區域則又增大為每上升 100 公尺氣溫下降 0.5~0.6˚C (夏禹九 2011)，這意味著峽谷內有著異常涼爽的氣候條件。究其原因可能是陡峭的地形使得此地在夜間冷空氣沿著山壁急速下沉至谷底(夏禹九 2011)，但白天又因日照不佳升溫較慢所致。今日蓮花池的海拔高度在 1,100 公尺左右，但太魯閣地區抬升與河流下切速率極快，若粗略以立霧溪向下侵蝕速率為每年 2.6 公分(Schaller et al.,2005)來計算，在發生新仙女木事件的 12,800 年前蓮花池的海拔高度可能只有 700 公尺左右，因此，當峽谷外的大氣環境變冷，將使得峽谷內的低溫現象更加明顯，並在蓮花池的花粉紀錄中留下清晰的變冷訊號。

太魯閣峽谷的獨特地形除了形塑出峽谷內相對涼爽的氣候特色外，更是造成當地出現多種特有生物的關鍵(陳添財 2022)。

臺灣水鹿(*Rusa unicolor swinhoii*)為臺灣特有亞種保育類野生動物，常見分布在海拔 1,500 至 2,500 公尺的山區。根據親緣地理學和分子時鐘的研究，台灣水鹿源自於亞洲大陸，與海南水鹿在距今 97 萬年前(141-55 萬年前)之前有著共同祖先。這群山友口中的「山神獸」在遺傳結構上可顯著分為南北兩大類群：太魯閣—雪霸類群(TS clade)和中央山脈類群(CMR clade)，兩類群的共同祖先出現在 41萬年前(63-21 萬年前)之前。依據基因網絡、親緣關係和近似貝頁式(DIYABC)分析結果，CMR 類群是台灣水鹿中的較古老型，原本棲息在中央山脈中段和南段山區，但在早於 41 萬年前(63-21 萬年前)的間冰期此族群曾向北擴散，並在後來的冰期裡除了南移之外，有一群水鹿向較低海拔區域降遷而進入太魯閣峽谷。由於峽谷地形造成地理隔閡，峽谷裡的水鹿經歷了很長時間的自然選拔淘汰，進而分化出與 CMR 祖先有所不同的 TS 類群(Li *et al*. 2023)。造成水鹿長期留滯於太魯閣峽谷以致遺傳結構出現分歧的原因，除了冰期時的地形隔離之外，推測也包括間冰期峽谷內相對涼爽的氣候條件創造了適合水鹿的棲息環境。

在生物地理學上，台灣因具有多種冰河孑遺生物而受到全球關注，這些動植物在更新世的冰河時期自北方南遷至台灣，並在氣候進入溫暖的間冰期時，受惠於台灣高山林立而轉向島上高海拔區域棲息，因此台灣不僅是這些北方動植物在今日全球空間分布上的南界，也說明在過去的冰河時期台灣曾經扮演生物庇護所的角色。然而在更新世反覆出現的冷暖循環裡，特別是類似今日全球暖化趨勢不斷加劇的間冰期，這些冰河孑遺生物除了往更高海拔地區尋找新的棲息地之外，也迫切需要氣候條件相對涼爽的場域以求存活，太魯閣峽谷相對涼爽的環境條件，正是面對氣候變遷的最佳生物庇護所。

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Epipelagic Gastropods From Southern Taiwan

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Abstract

Holoplanktic gastropods are ubiquitous across all oceans and predominantly inhabiting the epipelagic waters. They comprise two distinct groups, pteropods (subclass Heterobranchia) and heteropods (subclass Caenogastropoda). Distinguished by their fragile aragonitic shells, holoplanktic snails serve as valuable proxy for environments, particularly to water temperature, salinity, and depth. However, the fragility of the shell poses challenges in their fossil preservation and identification, particularly given their slight morphological differences within closely related taxa. In Indo-West Pacific, their fossils are mainly from the Neogene localities in Japan, along with two reports from the Philippines (Pliocene) and from China (Eocene). In Taiwan, their records remain scarce, with one study noting their presence in northern Taiwan's Oligocene deposits. Here, we present new findings of holoplanktic gastropods from the bulk sediment samples of the Late Pleistocene Szekou Formation in southern Taiwan, contributing to the understanding of their distribution and diversity in the region. We identified over 10 pteropod and 3 heteropod species. The predominance of species typical of subtropical and tropical regions, with no indication of deep-water preferences, supports the notion of a shallow-water environment in the Szekou Formation, as previously documented. Our ongoing research involves investigating additional locations and interpreting their paleoenvironments to elucidate Taiwan's role in the settlement of their diversity through time.

更新世晚期臺灣南部恆春西臺地腕足動物及軟體動物化石殼體化學成份反映之古環境

Late Pleistocene environment of the west Hengchun Hill, Taiwan inferred from chemical compositions of fossil brachiopod and mollusk shells

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摘　要

我們整理了恆春地區貓鼻頭剖面及頭溝剖面共14個層位的腕足動物化石（*Pictothyris picta*、*Lequeus orbicularis*、*Kikaithyris hanzawai*）、採自三溝剖面的四溝層血蚶（*Anadara granosa*）、圓象牙貝（ *Fissidentalium verneidei*）及錐螺（*Turritella sp.*）等軟體動物化石殼體的穩定碳氧同位素及元素含量數據，嘗試了解更新世晚期恆春西臺地的古環境。

我們根據化石殼體的礦物組成、原始微細構造、陰極射線顯微鏡下之發光特性及Mn、Fe、Al、Si等微量元素含量的特性來確認標本保存狀況。保存良好的腕足動物殼體的$\delta^{18}O$數值介於-0.6至1.1‰之間（0.2 ± 0.3‰；平均值 ±1σ；N = 175），$\delta^{13}C$數值介於-0.2至2.6‰之間（1.4 ± 0.6‰）。採自三溝剖面下部四溝層血蚶化石的$\delta^{18}O$數值介於-2.5‰至0.9‰之間（-0.6 ± 0.7‰；N = 82），$\delta^{13}C$數值介於-5.0‰至-2.5‰之間（-3.6 ± 0.7‰）；上部四溝層血蚶化石的$\delta^{18}O$數值介於-1.9‰至0.5‰之間（-0.7 ± 0.7‰；N = 47），$\delta^{13}C$數值介於-4.2‰至-1.3‰之間（-2.6 ± 0.8‰）。採自三溝剖面下部四溝層圓象牙貝化石的$\delta^{18}O$數值介於0.1‰至1.1‰之間（0.5 ± 0.3‰；N = 41），$\delta^{13}C$數值介於1.5‰至2.5‰之間（1.8 ± 0.3‰）。 採自三溝剖面下部四溝層錐螺化石的$\delta^{18}O$數值介於-0.7‰至0.7‰之間（0.1 ± 0.4‰；N = 42），$\delta^{13}C$數值介於1.1‰至3.0‰之間（2.2±0.4‰）。

根據採樣層位分布較多的腕足動物化石殼體紀錄，貓鼻頭及頭溝恆春石灰岩腕足動物殼體的平均氧同位素數值比頭溝四溝層腕足動物殼體的平均氧同位素數值大~0.4‰，雖然有地層對比之不確定性，三溝剖面下部四溝層圓象牙貝及錐螺化石的穩定碳氧同位素數值與頭溝下部四溝層腕足動物殼體的穩定碳氧同位素數值相近，若該地區的溫度變化不大，則恆春石灰岩較偏向形成於冰期時之環境狀態。

三溝剖面下部四溝層與上部四溝層血蚶化石殼體的氧同位素數值無顯著的差異，血蚶化石的採集層位亦不易與頭溝四溝層比對。但由於兩個層位的血蚶化石殼體的碳、氧同位素數值分布均呈現正線性相關，顯示在三溝剖面四溝層沉積時，瀉湖水體受到顯著不同程度淡水與海水混合的影響。

臺灣南部恆春西台地貓鼻頭石灰岩層序地層與沉積環境

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摘 要

恆春半島蘊涵臺灣造山作用最年輕一期的層序，增積岩體在劇烈抬升的過程中，發育相當規模的碳酸鹽岩覆蓋在海相沉積岩之上。其中恆春斷層以西的恆春西台地，為一第四紀隆起且西高東低的台地，於現今海平面之上主要由更新世的地層所組成。在恆春西台地南端海岸出露
的貓鼻頭石灰岩相較其他地點的恆春石灰岩具有獨特岩相組成，其普遍存在的大型交錯層在過去的沉積環境解釋中就有不同見解。經由野外調查，近乎水平層理的貓鼻頭石灰岩自海水面以上出露厚度可達 37m，且岩層中主要發現的沉積構造多為圓丘狀交錯層理（hummocky or swaley cross-stratification，簡稱 HCS/SCS）。

貓鼻頭石灰岩主要可分為三種岩相：（一）生物碎屑泥粒灰岩（Bioclastic Packstone Lithofacies）、（二）生物碎屑泥粒-顆粒灰岩（Bioclastic Packstone-Grainstone Lithofacies）和（三）生物碎屑顆粒灰岩（Bioclastic Grainstone Lithofacies）。岩層中的碳酸鹽顆粒主要由生物碎屑組成，一般小於2mm，多屬於顆粒支持的碎屑性石灰岩。顆粒間在交錯層內有明顯排列，大型生物殼體如藤壺、海膽、貝類等磨損程度高，顯示在強烈水流下被搬運和迅速堆積。而從其較小型化石的埋藏狀況中，發現浮游性有孔蟲，和大型有孔蟲、小型底棲性有孔蟲、苔蘚蟲等混合的生物殼體，可能指示沉積物曾經過水流翻動，擾亂海床沉積物使兩者混合。此
外，於交錯層底部也曾發現生物擾動現象。依照超微化石與浮游性有孔蟲分析結果，貓鼻頭石灰岩的生物地層帶相當於 NN19 和 N22 化石帶，其沉積年代可能介於 1.7Ma 與 0.61Ma 之間。總結岩相組合和特性，本研究認為貓鼻頭石灰岩是暴風環境為主的產物，經高能量的波浪作用搬運、並經由快速沉積所形成的再積石灰岩（redeposited limestone）。

關鍵字：恆春西台地、恆春石灰岩、貓鼻頭石灰岩、沉積環境、圓丘狀交錯層理

台灣通用岩盤模型建立及應用

Construction of the Taiwan Generic Rock (TWGR) Velocity Profile and Its Application

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現今絕大部分的地動模型（GMM）都使用 V_{S30}（近地表 30 公尺平均剪力波速）作為場址效應參數，但理論上僅考慮 30 公尺地層的波速並無法完整地表現出某個測站的場址效應，V_{S30} 之所以能夠有效反應場址效應乃是因為它和深部真正控制場址效應的 $V_S(z)$特性具有高度相關性，然而此 V_{S30} - $V_S(z)$的關係在不同區域並不相同，故某地區基於 V_{S30} 的放大模型並不能適用於其他地區。台灣是全球地震最為活躍的區域之一，並擁有最高密度的強震觀測網，能提供豐富的強震記錄，這些數據對於強地動特性及地動模型（GMMs）的相關研究都相當重要。我們最近的研究（Kuo and Abrahamson, 2023）提出一個符合工程岩盤（V_{S30} = 760 公尺 /s）條件的台灣通用岩盤（Taiwan Generic Rock, TWGR）模型，以提高對台灣強震資料的理解和增加使用時的合理性，並有助於改進基於這些強震資料的地動模型。從許多已發表的研究結果收集速度剖面資訊，涵蓋從地表到 16 公里深度的範圍，資料來源包括強震站的速度井測以及其他不同解析深度的地震學相關研究成果。我們使用這些資料進行分析並提出一個通用岩盤剪力波速度（V_S）剖面，其深度延伸至地震基盤（V_S = 3.5 公里/秒），同時也提供了對應的高頻衰減參數κ_0及通用岩盤 P 波速度（V_P）剖面。TWGR 能應用在許多工程地震學相關研究，如搭配震波數值模擬產製均布危害度反應譜（UHRS），或使用速度修正法進行更準確的地盤反應分析等。

關鍵字：工程岩盤、V_{S30}、台灣通用岩盤
Keyword: Engineering bedrock, V_{S30}, TWGR

投稿議題：S2 - 工程地震學 Engineering Seismology

Why Did The Pulse-Like Ground-Motions Differ Three Times in PGV and Tp Within A 3 km Wide Near-Fault Region of The 2023 Mw7.8 Turkiye Earthquake?

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Abstract

Over 25 pulse-like velocity (VP) waveforms were observed in the near-fault region of the 2023 Turkiye Mw 7.8 earthquake, which were extracted by Shahi and Baker's (2014) method. The extracted VPs have a peak ground velocity (PGV) and pulse period (Tp) range of 25 to 184.2 cm/s and 1.8 to 15.6 s, respectively, which were in a rupture distance (Rrup) range of 0.33 to 54 km. Significant intensity differences in the VP were observed at three stations within a 3 km wide near-fault region, Antakya, one of the major disaster regions, and observed as the second-largest PGV of the extracted VPs. The Rrup of the three stations is 0.33, 2.1, and 3.5 km for stations 3126, 3123, and 3131, respectively. However, the corresponding extracted PGV and Tp showed a two- to three-times difference within the three stations from PGV of 119.9, 175.4, and 60.3 cm/s and Tp of 3.4, 2.6, and 13.2 s. This is difficult to explain by the median prediction of the modern nonergodic ground motion models. By removing a possible cause from the coseismic static offset (fling step), the directivity pulse is evaluated by the VP simulation procedure (Huang et al., 2024), which is derived from the stochastic finite-fault ground-motion simulation method, a baseline correction method, and a fling-step removal model. The result indicated that the directivity pulse provides a 50 to 60 cm/s PGV, which was recorded by the rock site 3131 and enlarged two times from linear site response and recorded by the softest soil site 3126. The three times PGV observed at 3123 was generated by simultaneously linear site response and a super shear behavior at the near-source portion. The closest station, 3126, did not suffer the highest PGV in this region because of the soil nonlinearity in the latter portion of the S arrival. Finally, the longest 13.2 s Tp is caused by a 130 cm coseismic deformation from the fling-step, which occurred after the VP arrival and did not show an apparent longer period in the other two stations.

Improving Earthquake Early Warning Initial Peak Ground Motion Magnitude Estimation with Station Corrections: A Case Study Using The P-Alert Network in Taiwan

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Earthquake early warning systems assess the size of an earthquake based on initial ground motion and provide warnings before the arrival of large waves. We employ the iterative regression to simultaneously estimate the station correlations and corresponding linear relations for magnitude. We report the standard error reductions of the magnitude estimation based on the initial peak P-wave acceleration (P_a), velocity (P_v), and displacement (P_d) as 14.52%, 7.63%, and 7.58%, respectively. Factor analysis of the station correction reveals its correlation with several factors. This study shows that station correction can help to improve the precision of magnitude estimation in the future.

A microservices-based scalable seismogram processing system for real-time seismology

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Abstract

In recent years, the growth of dense seismic networks has enhanced the ability to detect microseismicity. However, the massive amount of the collected data poses manual data processing and analysis challenges. Developing reliable and efficient algorithms for seismic monitoring is thus crucial for studying seismic-induced structures and hazard mitigation. The recent advances in seismogram processing take advantage of deep learning, which could differ greatly in model input format (e.g., time-series data, spectrogram data, station geometry, various vector sizes, etc.). Most importantly, deep learning algorithms are growing rapidly, and the frequent substitution of algorithms into the workflow is expected. Constructing a microservices-based data processing system can solve the issues of multivariant input and message transfer between different services. Here, we introduce our microservices-based seismogram processing system that can scale up the services when the computing resources are limited to a single node. All modules work in parallel. With an Intel Xeon W-2125 8-core CPU and an RTX 2080 Ti GPU, we demonstrate the capability of our system with both the real-time earthquake early warning use case and the near real-time earthquake cataloging during the 2022 Guanshan-Chihshang earthquake period. The data packet streaming module is based on the MQTT protocol, which is currently adopted by the Central Weather Agency (CWA) in the real-time system. The products of each module are queued and transmitted using Kafka. Our system processes the data packet and does real-time phase-picking (reporting P arrivals before the S phase as soon as possible) using the RED-PAN model for 917 stations' three-component data. The detected P arrivals are then sent to the Equal Differential Time (EDT) algorithm for the real-time hypocenter location. For the tracked P and S arrivals, we test the utility of different phase associators for regular earthquake cataloging.

Key words: microservices, real-time seismology, deep learning

Constraining Seismic Anisotropy Beneath Southern Taiwan: Insights from SKS/SKKS Splitting Analysis with the SALUTE Array

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Abstract:

The Taiwan orogen is a unique result of oblique convergence between the WSW-ENE trending Chinese continental margin of the Eurasian Plate (EUP) and the N-S trending Luzon Volcanic Arc (LVA) of the Philippine Sea Plate (PSP). Shear-wave splitting analysis, a prevalent method is employed to deduce two crucial parameters: the fast polarization direction, indicating the preferred alignment of fractures, and the direction of maximum horizontal stress or mantle flow. The other parameter is the delay time, characterizes the degree of anisotropy and the thickness of the anisotropic layer. This study primarily focuses on determining SKS/SKKS splitting parameters, utilizing teleseismic earthquake data in the distance range of 85-140 degrees recorded by the Southern Array for the Lithosphere and Uplift of Taiwan Experiment (SALUTE) between Dec. 2021 and Oct. 2023. The SALUTE array consists of 30 closely spaced broadband stations strategically deployed across southern Taiwan, transitioning from continental subduction to oceanic arc collision. The analysis employs the widely recognized and extensively used MATLAB tool, SplitLab (Wustefeld et al., 2008), to comprehensively analyze splitting parameter measurements for individual seismic events. Additionally, a multi-event approach is adopted to enhance the accuracy and stability of shear wave splitting results. In this approach, events with similar backazimuths are grouped into four quadrants, and the methods of error surface stacking (WS, Wolfe and Silver, 1998) and normalized surface stacking weighted by signal-to-noise ratios (RH, Restivo and Helffrich, 1999) are applied using another MATLAB tool, StackSplit (Grund, 2017), to obtain robust splitting parameters with significantly reduced uncertainties. Measurements are categorized as good, fair, or poor based on the same quality criteria outlined in SplitLab. The good and fair results indicate that observed fast polarization azimuths are predominantly within ±25° from north, and delay times range from 1.5 to 2.5 s. This suggests that both orogen-subparallel shear deformation in the lithospheric domain and toroidal asthenospheric flow induced by the quasi-orthogonal subduction of the PSP and EUP may contribute to observed seismic anisotropy in southern Taiwan.

Keywords: Southern Taiwan, Shear wave splitting, Splitlab, SALUTE Array, toroidal flow

嘉義地區短周期地震網之建置與研究

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摘　要

嘉義地區的麓山帶有複雜的斷層系統，不僅存在臺灣常見的逆衝斷層，還包括橫移斷層，及潛伏在沖積平原底下的盲斷層。值得注意的是，這三種不同類型的斷層，地表破裂形式和災情分佈等特性各不相同。我們需要評估每條斷層的活動程度及相互關聯性，以了解是否可能會彼此相互觸發活動，導致更為嚴重的災情。為了增進對嘉義地區地震活動特性的了解，根據現有觀測的地震活動和斷層分佈情形，選定18個地點，設置了密集的短周期臨時地震觀測網。於西元2021年10月初步完成建置，並逐漸改善測站配置，主要使用太陽能板和電池供電，規劃約每4個月進行測站維護與資料下載。從西元2023年11月開始，在其中6個站裝設即時傳輸設備，並搭配中研院地球所與中正大學地環系的寬頻站，共同監測雲嘉南及附近的地震活動。觀測期間，除了西部山麓帶及阿里山山區持續發生規模3以下的地震之外，平原區也發生了兩個顯著的有感地震序列，如西元2023年8-9月的新港-民雄地震序列，以及西元2024年2-3月的太保-朴子地震序列等。

未來將試著整合其他觀測網的測站，以增加測站密度並改善側向解析力。透過地震定位及震源機制解解算，希望可以了解背景地震活動情形。同時利用環境背景雜訊分析技術，探求淺部地殼速度模型。並進一步綜合判斷嘉義地區的地震活動潛勢，了解各斷層的活動度並建立相關參數，提供後續地動潛勢和災損評估的基本參考依據，期望能減輕下次地震可能帶來的危害。

Characteristics and Mechanical Insight of the 2023 Hsinkung Earthquake Sequence

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We deployed a dense seismic array to capture the seismic characteristics before and after the Ml=5.5 Hsinkung earthquake on September 5th. We found that the 2023 Hsinkung earthquake sequence follows an ancient liquefaction lineation during the 1906 Meishan earthquake. Before the mainshock, a distinct spatial jump of foreshocks formed a seismic gap and induced stress concentration at the boundary of the gap. After that, foreshocks progressively migrated from the gap border toward its center. This uni-direction earthquake migration implies crack growth, which increased the stress intensity factor and led to a catastrophic ruputre during the mainshock when the stress intensity factor reached the fracture toughness.

Is the Pre-Cenozoic basement of Taiwan strait an exotic terrane? : Constraints from detrital zircon and monazite U-Pb ages of Well TL-1 in Penghu Island

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Abstract

The Pre-Cenozoic basement beneath the Taiwan Strait (TS) and East China Sea (ECS), considered an extension of the East Cathaysia Block (ECB), remains poorly understood with limited investigation into its crustal compositions. This study focuses on Well TL-1, a 900-meter-deep core on Penghu Island, employing coupled detrital zircon and monazite U-Pb ages of littoral-to-neritic facies sediments. The aim is to elucidate the crustal characteristics of the TS basement and its relationship with ECB. Below an unconformity at depth of 503 meters, five Early Cretaceous sand-siltstones exhibit a distinctive zircon age cluster of approximately 120 Ma with minor Early Jurassic (ca. 190 Ma) inherited grains. These ages align with major magmatic episodes observed in the ECS basement. Positive ƐHf(t) features of these Jurassic-Cretaceous zircons suggest mantle-origin magmatism, contrasting with the Mesozoic crustal assimilation magmatic system in ECB. On the other hand, zircon age spectra from two Early Miocene sediments at depths of 403 and 500 meters reveal four groups, including ca. 1.8 Ga, 800-700 Ma, 450-430 Ma, and 300-200 Ma, consistent with common deposits in ECS and the drainage systems of ECB. Notably, the presence of 1.8 Ga monazites (30-45%) in these samples, absent from neighboring continents, indicates an exotic provenance. The large grain sizes (larger than 100 microns) and euhedral to subhedral morphology of these monazites further suggest a proximal source-sink relationship for the Miocene sediments. In summary, the features observed in Well TL-1 deposits suggest a potential disconnection between TS and ECB crusts, implying the concept of an allochthonous terrane. Additionally, the application of dual-mineral geochronology to sediments proves valuable in providing comprehensive information on source areas.

Keywords: Detrital zircon and monazite, U-Pb ages, pre-Cenozoic basement, exotic terrane, Taiwan Strait

Tracking the progressive stages of alteration in serpentinites – an integrated petro-geochemical study from Andaman Ophiolite, SE Asia

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Abstract

Serpentinite and serpentinized peridotite are common in the mantle section of ophiolite stratigraphy. They are thought to have formed by the interaction of the forearc mantle with aqueous fluids released from altered oceanic crust and sediments. In this process normal mantle minerals are usually converted into serpentine group minerals (hence serpentinization); however, the underlying mechanism of it and the nature of the fluid remain poorly understood. Here, we report a detailed petrologic and geochemical study of a serpentinized peridotite section from the Andaman Ophiolite, SE Asia. At the outcrop scale, narrow zones having a distinctive colour and width of ~20-80 cm were identified within the serpentinite body. The dominant portion of the outcrop is moderately serpentinized lherzolite with variably preserved olivine, orthopyroxene and clinopyroxene while the narrow zones show evidence of near-complete serpentinization. Intermediate stages in terms of alteration degree were also observed among the studied samples. Despite that, another notable observation is that chrome-spinel is almost absent in all samples, presumably underwent a pseudomorphic transformation into a silicate+oxide assemblage of uvarovite(?) ± chlorite ± Cr-magnetite(?). The reaction might have also formed Ti-rich andradite from clinopyroxene, suggesting the probable introduction of oxidizing Ca-Ti-rich fluids from a source nearby. Comparing mineral and bulk rock chemistry, we suggest that different extents of fluid influx into and its reaction with the same spinel lherzolite protolith might be responsible for the formation of the narrow zones (as a highly altered channel) in the pervasive fluid flow, providing an opportunity to examine the mineralogical and geochemical changes associated with progressive stages and/or flow regimes of serpentinization.

Detrital zircon U-Pb geochronology on Matsu beach sands: the depositional signature of small mountainous islands

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Abstract

The sediment source-to-sink processes of small mountainous islands lacking obvious drainage systems present an intriguing subject for investigation, yet few studies have focused on this topic. The Matsu Islands, situated approximately 15 km off the coast of South China, offer a compelling opportunity to explore this relationship. In this study, we concentrate on the two largest islands within the Matsu archipelago: Nangan (南竿, ~10.4 km^2) and Beigan (北竿, ~6.4 km^2), with three samples systematically collected from each. Analysis of the detrital zircon U-Pb age spectra reveals a striking similarity among most samples, aligning well with reported radiometric ages of the islands' crystalline rocks. Notably, Qinbi (芹壁) beach sands exhibit a monomodal age spectrum, with the peak age closely resembling radiometric ages reported from nearby Bishan (壁山). This deviation suggests that Qinbi beach sands are primarily derived from the adjacent area, while the remaining beaches predominantly derive their sediment from various crystalline rocks within the islands.

The detrital zircon age spectra of Matsu beach sands contrasts with those found in Minjiang river sands. In Minjiang river sands, Indosinian and Caledonian ages are more prevalent, nearly equal in abundance to Yanshanian ages. This discrepancy may be attributed to the increased presence of reworked zircons within Minjiang river sands. Furthermore, comparison with sands found on beaches and rivers in Taiwan reveals a higher abundance of zircons with Jinning, Sibao, Luliang, and Wutai ages, indicating significant zircon reworking within Taiwanese sediments. Therefore, it is unlikely for the Minjiang to serve as the primary sedimentary source for Taiwanese sediments. In summary, our study suggests that Matsu beach sands are primarily sourced from the islands themselves, with minimal contribution from the Minjiang river. Additionally, Minjiang may not be an important sedimentary source to Taiwan as previously suggested.

Zircon U-Th-Pb Geochronology using the LA-ICP-MS/MS at National Taiwan Normal University

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The LA-ICP-MS/MS facility at the Department of Earth Science, National Taiwan Normal University, Taiwan houses a 193 nm ArF Analyte Excimer Plus laser ablation system (Teledyne CETAC) coupled with Agilent 8900 quadrupole mass spectrometer (ICP-QQQ-MS). Two quadrupoles in the Agilent 8900 act as mass filters. A reaction cell is also placed between these two quadrupoles. Currently, the focus of the facility is to carry out zircon U-Th-Pb isotope analyses. For the zircon U-Th-Pb geochronology, the samples are ablated with the laser in the HelEx II sample cell with helium as the carrier gas. The ablated sample aerosol and helium carrier gas are then mixed with argon make-up gas in a co-axial mixing adapter directly connected to the ICP touch and then transported to the ICP-MS/MS. The main advantage of the reaction cell in the Agilent 8900 quadrupole mass spectrometer for zircon U-Th-Pb geochronology is that the isobaric interference of ^{204}Hg on ^{204}Pb can be reduced using a gas-phase charge transfer reaction with NH_3 reaction gas. Different spot sizes of 15, 20, 25, and 30 μm can also be used for the analyses. Both the laser system and ICP-MS/MS are optimized according to the widely accepted community-derived standards. The data reduction is conducted using the Iolite software. 91500 zircon and NIST SRM 610 glass reference materials are used as the primary reference materials, while Plešovice, AS3, and OD3 zircon standards are used as the secondary reference materials for the analyses. All the standards yielded U-Pb ages consistent with the ages reported by previous studies. Unknown zircons from the Panjal Traps (rhyolite) and Seychelles (syenite) yielded ages consistent with those ages reported previously using the high-resolution ID-TIMS (Isotope Dilution Thermal Ionization Mass Spectrometry).

Extrusion tectonism of Indochina reassessed: Constraints from $^{40}Ar/^{39}Ar$ geochronology from the Day Nui Con Voi metamorphic massif, Vietnam

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The extrusion tectonic model for southeastern margin of the Himalayan orogeny links the crustal shear activity along the Red River Shear Zone (RRSZ) to the opening of the South China Sea (SCS). The Day Nui Con Voi (DNCV) metamorphic massif in northern Vietnam strikes NW-SE, is bounded by the RRSZ to the south and continues along strike where it meets the SCS. The DNCV is thus a critical area to document the thermotectonic history in order to advance our understanding of the tectonic evolution of Indochina extrusion and its relationship to the opening of the SCS. Our new $^{40}Ar/^{39}Ar$ data combined with microstructural and petrological analyses constrain the timing of the left-lateral shearing of the RRSZ and revealed the thermal evolution of the DNCV metamorphic massif. Three ductile deformation events are observed. D_1 formed NNW-SSE striking upright folds under granulite to upper amphibolite facies conditions. D_2 is a horizontal to sub-horizontal folding event that occurred at amphibolite facies conditions. D_3 is a doming event that formed NW-SE striking up-right fold bounded by left-lateral shearing mylonite belts along the two limbs. The S/C fabrics are defined by muscovite fish, quartz + albite + K-feldspar aggregates and muscovite folia. The D_3 doming event exhumed the DNCV metamorphic massif from amphibolite facies conditions to the lower greenschist facies conditions. The $^{40}Ar/^{39}Ar$ ages obtained from amphibole (~26 Ma), phlogopite (~25 Ma), muscovites (~24-23 Ma), biotite (~25-23 Ma), and K-feldspars (~25-22 Ma) from different structural domains of the DNCV metamorphic massif indicated a rapid exhumation ~ 26-22 Ma. We interpreted this as the time period for the D_3 event, with the onset of left-lateral shearing occurring around 24 Ma based on ages obtained from syn-kinematic muscovites. This age is much younger than the initiation of sea-floor spreading of the SCS (since 32 Ma), but coincides with the age for the ridge jump event in the SCS. Based on these new data, we propose that the extrusion tectonism cannot be the cause for the initial opening of the SCS. Rather, the extrusion of the Indochina block is temporally correlative with the southward ridge jump event of the already opened SCS.

Middle Permian intraoceanic magmatism recorded in picrite-basalt associations along a Paleo-Tethyan suture, NE Iran

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Abstract

Primitive volcanic rocks exposed along sutures in orogenic belts provide rare but important geological records of mantle-derived magmatism that might have pre-dated orogeny. In this study, we report an association of picrites and basalts from the Fariman complex, northeastern Iran, likely formed by intraplate magmatism associated with the Paleo-Tethys in the Middle Permian. Mantle potential temperatures derived from the most primitive melt compositions range from 1472 ℃ to 1533 ℃, indicating an anomalously hot mantle source compared with MORB sources. Most melt generation likely occurred in the garnet stability field although the column of mantle melting might have extended towards the spinel-stable depths. In terms of parental melt compositions, Sr-Nd isotopic compositions, and mineral compositions, the picrite-basalt associations compare closely to localities that were affected by intraoceanic hotspot magmatism worldwide. Ongoing work sets to assess the mantle source characteristics and melting processes responsible for magma generation on the basis of this unique record of Paleotethyan intraplate magmatism.

Cenozoic Terrain Accretion from East China Sea to South China Sea Margins: A Perspective from Detrital Zircon Geochronology

由碎屑鋯石年代學探討新生代東海到南海大陸邊緣的地塊增生

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Abstract

The Cenozoic accretion of terrains associated with the opening of the South China Sea has been a topic of extensive debate. Previous geological observations and plate reconstructions have indicated the drift of several micro-continental blocks from the South China margin to their current positions following the Oligocene seafloor spreading of the South China Sea. Recent detrital zircon studies have provided further support through correlations based on zircon age spectra. Eocene strata from North Palawan and North Mindoro exhibit striking similarities to contemporary samples from the northeastern South China Sea region, suggesting a potential conjugate relationship with the eastern Pearl River Mouth Basin (PRMB). New detrital U-Pb data from Late Eocene strata in the East China Sea Shelf Basin (ECSSB) reveal a significant peak around ~1.85 Ga, distinct from the age spectra of PRMB but closely resembling that of North Mindoro. This suggests a possible conjugate margin relationship between North Mindoro and ECSSB. However, a notable gap exists between pre-drifted North Palawan and North Mindoro. Considering the potential existence of a ribbon continent beneath the current North Luzon Arc, which has collided with the South China continental margin at Taiwan, we conducted new detrital zircon analyses from East Taiwan, as well as from the western and southwestern offshore regions of Taiwan, and compiled existing detrital zircon data from the East China Sea to South China Sea margins to address this issue comprehensively. Our findings indicate that both North Mindoro and the ribbon continent beneath East Taiwan originate from the ECSSB. North Mindoro likely reached its current position through southward movement along an N-S trending transform fault, while the ribbon continent was thrust beneath East Taiwan by the advancing North Luzon Arc. These results align well with recent detrital zircon and paleomagnetic studies from ODP site 1177A.

關鍵字：地塊增生、碎屑鋯石年代學、東海、南海
Keywords: Terrain accretion, detrital zircon geochronology, East China Sea, and South China Sea

濁水溪沖積扇臺地周緣水文地質架構研析

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摘　要

八卦臺地與斗六丘陵位於濁水溪沖積扇的南北扇之東側，受到地質構造作用而隆起，出露著以上新世至更新世的地層為主，岩性為孔隙率高的礫石與砂岩，其地勢與岩層有利於地下水的流動與側向補注至濁水溪沖積扇；然而，臺地丘陵區及其周緣的平原區缺乏完善的水文地質資料，進而影響該區域的地下水蘊含量及補注機制之研究。因此，本研究於民國110年至112年完成34處補充水文地質鑽探與試驗，總進尺達3,090公尺，冀期建置濁水溪沖積臺地周緣的水文地質架構。

研究成果顯示，透過補充及既有的鑽井與既有水文地質剖面，於濁水溪沖積扇南扇可新增8條的水文地質剖面圖之繪製，進而掌握了阻水層T1的分布，以及修正既有石榴至芳草之剖面，更提供補注邊界之修正依據；另外，雲林縣平和、田頭、社口、東和等站，補足該區域的水文地質剖面資訊，以瞭解麓山帶與平原區之交界情形。而濁水溪沖積扇北扇，可編修3條既有的南北向剖面及新增4條東西向的剖面，以補足過去既有剖面在扇頂區與補注邊界之間所缺乏的資料，以釐清阻水層T1的尖滅位置，建議可往上游區進行微調修正；另外，在扇央區缺乏的地質資料中，如彰化縣大村、埔鹽、埔心、社頭、田尾及北斗等地區，完成含水層F1至F2及阻水層T1至T2的地層對比。

本研究建議後續可於各剖面之間新增深井，以釐清各含水層的延續性，尤其研究臺地西側與平原區之交界帶的關聯性，目前透過村東與山湖站可瞭解頭嵙山礫石層與平原區的交界分布，受彰化斷層影響，北側斷層面約有15度的傾斜，愈往南側角度則愈大，使得北側與南側近斷層帶中形成一交錯面，而中段近員林地區的礫石層可延伸至斷層帶西側的平原區。此外，建議彙整相關的井測及抽水試驗等成果，以釐清含水層的分布特性，進而提供水資源開發與管理政策之參考。

關鍵字：濁水溪沖積扇、臺地、地下水、水文地質

Keywords: Zhuoshui River Alluvial Fan, terrace, ground water, hydrogeology

裂隙岩體受尺度效應影響之水力特性

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摘　要

為因應地下水資源調查、地熱資源開發及碳封存等諸多議題，水文地質結合岩體工程已然成為必要之工程規劃。然而裂隙岩體具異質性及異向性，不連續面發展縱橫使水力特性調查困難且變異性高，使得區域岩體滲透特性難以適當描述。為解決此問題，本研究透過推導裂隙岩體水力傳導係數理論式 (Oda, 1985)，以誤差傳播理論作為基礎，探討尺度對於水力傳導係數的影響程度，藉此定義代表性單元體積以描述整體水力特性。研究更應用於南投和社井場 (Zhan *et al*., 2016)，成果顯示，當尺度越大，水力傳導係數變異程度趨緩，可視當岩體尺寸大於 14 m為和社場址之代表性單元體積。

關鍵字: 水力傳導係數張量、代表性單元體積、尺度效應

濁水溪沖積扇地下水鹽化調查及初步分析

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摘　要

探討沿岸含水層系統受到的鹽化現象，多以地層的地下水受「側向」海水入侵為主，例如屏東平原，受因於人為抽水加速淡海水介面向內陸移動，此為「海水入侵」現象。現今，利用地質鑽探調查，已初步釐清臺灣本島地下水分區之地下地質環境，並建立水文地質架構模型。而在地下水資源利用的重點區域，如濁水溪流域，研究顯示西南沿海有地下水鹽化之趨勢，由於濁水溪流域之含水層於沖積扇的扇端尖滅，代表地下含水層未與海水相連通，故其含水層鹽化主要是受到地表的來源，由上向下之海水倒灌或人為污染的可能性較高。

水利署歷史數據自1992年「臺灣地區地下水觀測網整體計畫」開始累積，然而早年數據有較多缺失，近年數據已有提高品質，但因地下水觀測井繁多導致採樣頻率較低，至多每年一筆，多數觀測井則為數年1筆，但仍可建立長時間尺度的時序演進；環境部自1994年「全國水質監測計畫」進行地下水監測，觀測井之深度集中在第1含水層，其標的為淺層地下水污染變動，故較水利署有更高的採樣頻率，但主要缺乏第2~4含水層之地下水樣分析資料，但對於乾濕季的水樣資料變動可提供參考。本研究初步統整前述2014至2022年之現地水化學數據統計結果，該地區之鹽化現象與鈣、鎂、鉀、鈉、氯鹽、硫酸鹽等參數有高相關性，且出現地下水鹽化現象之井多集中於西南沿海之第1及第2含水層，第3及第4含水層則無鹽化特徵。

本研究初步探討濁水溪地下水鹽化於時序上的演變，另補充調查鹽化區位之採樣頻率，於每年乾季末 (約5月) 及雨季末 (約11月) 至濁水溪西南側沿海地區各採樣1次，以獲得具有最大乾濕季特徵之樣品，並將兩季採樣之代表性結果加以比對，有助於釐清季節性對於地下水鹽化之特徵關係。現地觀測井採樣數值顯示：雨季期間，鄰近西南沿海或北港溪鄰近的高鹽化區域，其鹽化指標並未下降，反而略有上升之趨勢，此概念有別於以往認為降雨作用後會淡化地下水質，推測事件型的海水倒灌後，使淺層鹽化土壤經降雨向下淋溶入滲有關，另觀測資料顯示，第1含水層受季節性的影響較第2含水層來的顯著，且位於已鹽化之區域，其濕季的鹽化指標有明顯的集中且上升之趨勢。未來，持續累積現地採樣資料，並建立量測多項水化學數值，如導電度、氯鹽、硫酸鹽、陰陽離子或氧化還原電位等，藉由多年期觀測數據，可建立場址之地下水鹽化調查成果，並以水化學演化圖 (HEF-D) 呈現海水入侵趨勢，以熱圖繪製於地理資訊系統，相關成果數據亦可供數值模擬之參數選定。

抗旱地下水找水潛力圖之建置與應用

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臺灣近年受到極端氣候的影響，常時不降雨使得區域性缺水成為常態化的問題，對於積極開發淡水水源，地下水的開發即成為最快且合於成本之抗旱備援最重要水源，如何有效且充分利用水文地質調查成果以進行地下水的開發與應用，實已達到科學數據如何轉化為民生應用之決策性層級。

國內水文地質調查資料係累積近 40 年水文地質鑽探、鑽探岩心沉積環境分析、定年分析與地電阻調研及大量野外地質調查所得之成果，並完整建置平原區地下水文地質概念模型、完整鑽探岩心柱狀圖空間分布，並依概念模型建置三維地層模型，以掌控地下水儲水層與阻水層之分布與延展；惟該模型以儲、阻水之岩性特徵為基礎，亦即代表建置平原區岩性及變化之空間分布，對於平原區乾旱常態化之找水工程，將起重要且關鍵性之助益。吾人知地下未膠結固結地層之富水層，其最佳岩性為礫石至極粗砂等粒徑之地層，對於抗旱找水而言，尤為最佳之目標層；其次粗砂至細砂層亦為優良之富水層，惟其厚度與富水效果不及前述；再者，粉砂至泥等粒徑地層為難透水層，縱其富含孔隙水，其低透水率仍難以提取，為抗旱找水最不利地層。綜上據以分類三維地層模型富水層之空間分布，則可綜觀某地下水分區內有利抗旱找水地下之空間分布。

就前述分類，併與抗旱找水之緊迫性與解旱目標，本研究就地表 200 公尺內地層分析與分類，地層富水層加總厚度達 100 米以上者，為抗旱找地下水高潛力區，加總厚度在 100 至 50 米間者為中潛力區，而低於 50 米以下者為低潛力區，為缺乏有效地下取水之處，然若單層厚度即可達 100 米以上者，可取水難度大減且效率更高，可列為特高潛力區。該潛勢分類則極為適合以蛋黃圖表現之，一目瞭然；若加之以投影至熟悉或常用之高精度地形底圖，則圈地、規劃、抗旱鑿井等，直為水到渠成。本研究潛力圖除了透過分級可快速瞭解平面空間上的儲水層分布位置與厚度外，亦可在預計開鑿抗旱井前，進一步地檢視區域地下地層的分布概況，及透過系統分析評估後，產生地下水井之建議的開篩深度，並可搭配實際水文地質鑽井岩性柱狀圖等資料進行綜合性的評估，作為實際開鑿抗旱井的取水深度與成本評估之參考；本研究成果於 110 年及 112 年乾旱年度，提供水利署、自來水公司及地方政府等單位鑽鑿抗旱地下水井之依據，其豐碩成果發揮了重大功效！

利用磁環分層式地層下陷監測井觀測資料解析臺灣濁水溪沖積扇的地層下陷潛勢特性

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摘　要

臺灣中部濁水溪沖積扇長期之地層下陷監測成果指出，近年之地層下陷速率在沖積扇北側的彰化地區已獲得改善，但是沖積扇南側的雲林地區卻仍大規模的發生。為了釐清造成兩個地區地層下陷模式差異的可能原因，本研究利用35口磁環分層式地層下陷監測井（MLCW）、83口地下水位監測井，以及4個深層水準樁的監測數據，探討濁水溪沖積扇水文地質特性對於地層下陷潛勢（susceptibility）的影響。為了彌補既有水文地質分析方法的限制，本研究嘗試提出新的水文地質特性分類方法。基於已知MLCW磁環紀錄和地下位季節性變化模式的一致性，本研究嘗試將焦點集中在地層壓密潛勢的物理特性分析。藉由計算兩個磁環時間序列的互相關係數（cross-correlation），本研究可以判定兩磁環間季節性波動型態的類似程度。

相似程度越高，則可假設兩磁環間的地下水是相互影響且高度可能是流通的（高敏感度；high sensitivity）。通過此方法，本研究可以計算單一MLCW不同深度磁環間之敏感度，建立各MLCW之垂直敏感度模型（vertical sensitivity model），並進一步計算兩兩MLCW間各磁環之敏感度，建立6個跨越扇頂至扇尾剖面之水平敏感度模型（horizontal sensitivity model），最後再採用內插法，利用6個剖面之水平敏感度模型，建立三維之區域水平敏感度模型。根據此模型及搭配地下水位與電性地層成果之交互比對，本研究揭示雲林地區與彰化地區間在固有材料性質及其對地下水抽取反應上的巨大差異。雲林地區之水文地質特性類似於一個「大海綿」的狀態，在此地區任何一個地方抽水，都有高度潛勢造成其他地區一同發生地層下陷。相反地，彰化地區的水文地質特性就如同一個個獨立且互不相關的孔隙，因此在單一地點進行抽水，並不容易造成其他地區發生地層下陷。綜上所述，本研究不僅加深了我們對地層下陷機制的理解，而且將可為減緩地層下陷提供不同的策略。

關鍵詞：地磁下陷、磁環分層式地層下陷監測井、互相關係數、敏感度模型

濁水溪沖積扇含水層系統之骨架比儲水係數時空特性研究

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摘　要

地層下陷是一個影響廣大的地質災害，包括可能引起水資源的枯竭與土地資源的流失、建築損壞和財物損失等。台灣的濁水溪沖積扇地區面臨嚴重地層下陷的問題，主要受到自然和人為因素引起的土體壓密所致。要深入瞭解含水層系統變形和孔隙水壓力之間的相關性，就得深入理解土水力學特性。本研究的目標是評估不同深度地層中骨架比儲水係數(skeletal specific storage coefficient, Ssk)的空間和時間變化，以了解地層下陷與地下水位變化之間的關係。研究中的儲水係數包括彈性骨架比儲水係數(Sske)和非彈性骨架比儲水係數(Sskv)，這兩係數隱含地層下陷的壓縮速度和可壓縮性。研究中蒐集水利署提供的38口地下水井和31個分層式地層下陷監測井資料，以地下水位變化資料和累積土體壓縮資料，透過線性迴歸分析來推估兩儲水係數值。研究結果顯示，儲水係數隨季節有所變化，枯水期估計值一般較高，第一分層和第四分層的彈性骨架比儲水係數值範圍分別為9.30×10^{-6} ~ 1.15×10^{-4} m^{-1}和8.60×10^{-6} ~ 8.50×10^{-5} m^{-1}；而豐水期則相對較低，第一層和第四層的值範圍分別為1.00×10^{-5} ~ 6.68×10^{-5} m^{-1}和8.10×10^{-6} ~ 5.00×10^{-5} m^{-1}。此外，不同位置和地層中的儲水係數，受到區域土水力學特性變化而存在差異，特別是濁水溪沖積扇的扇央區域具有最高的儲水係數值，表示該區域比其他地區具有更容易壓密的特性。當含水層系統孔隙水壓下降時，該地區具有相當高的地層下陷潛勢。本研究展示了儲水係數在濁水溪沖積扇的時空變化特性，該成果可評估濁水溪沖積扇地區的地層下陷潛勢，並有助於該地區的地下水資源管理。

關鍵詞：彈性骨架比儲水係數、非彈性骨架比儲水係數、地下水位變化、土體壓密、地層下陷潛勢、濁水溪沖積扇。

Implementation of Distributed Fiber Optic Sensing Based on Brillouin Optical Time Domain Analysis for Land Subsidence Monitoring

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Abstract:

Land subsidence, caused by natural and human factors, poses risks to the environment and infrastructure worldwide. Monitoring it is challenging. This study presents a new method using distributed fiber optic sensors (DFOS) with Brillouin optical time domain reflectometry (BOTDR) to understand subsidence better. The model measures changes in fiber sinking rings, providing meter-scale resolution for studying stratum deformation. With a spatial resolution of 0.04m, BOTDR ensures precise measurements. Results reveal deformation patterns and contributors to subsidence. The DFOS model offers consistent long-term monitoring. This highlights DFOS as a valuable tool for understanding subsurface deformation and addressing land subsidence, especially in coastal areas.

Keywords: Land subsidence, Brillouin optical time domain reflectometry, Distributed fiber optic sensing

Introduction:

On the designs of saw-cut sample assemblies of rock triaxial tests

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Abstract

Over the past decades, the fields of seismology and geodesy have identified a wide spectrum of fault-slip behaviors has been identified, such as “slow-slip events (SSEs)”, tremors, low-frequency events (LFEs), and very-low-frequency events (VLFEs). However, the underlying mechanisms of these phenomena and the favorable frictional behaviors of fault rocks have not yet been fully unraveled. To better understand what pressure and temperature conditions may facilitate different fault-slip behaviors, we propose a saw-cut sample assembly for triaxial friction experiments on the GCTS servo-controlled Triaxial Rock Testing System (GCTS RTX-1000) at NCU. To simulate the fault-rock behaviors at depths, we will apply confining pressure (Pc) up to 70 MPa, pore-fluid pressure (Pp) up to 70 MPa, and temperature (T) up to 250˚C. To maintain the gouge thickness between the stainless-steel sliding blocks, we 3D-printed an auxiliary tool that could hold the sliding blocks and spread the gouge powder horizontally. The main challenge was the incompatibility between the dimension of the sample holder and that of the sliding blocks assembled with a heat-shrink jacket. Another difficulty was the degree of saturation of fault gouge, where excess water led to extrusion of the slurry gouge, while insufficient amount of water caused extra friction that offsets the filter paper sandwiched between the gouge sample and the sliding blocks. Our experimental methods mark the initiation of the very first triaxial friction experiments under various Pc, Pp, and T conditions in Taiwan. We anticipate the results to be broadly contributed to earthquake physics, as well as the explorations of sustainable energy, such as Enhanced Geothermal System (EGS) and Carbon Capture, Utilization and Storage (CCUS).

建置雷射加熱技術並結合高壓鑽石砧以模擬地球內部高溫高壓狀態

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摘　要

地球內部組成物質的熱傳導特性對於理解地球的熱演化和熱能收支非常重要。我們過去已透過高壓鑽石砧(DAC)及時域熱反射技術(TDTR)得到許多地函和地核組成材料在室溫高壓下的熱傳導率。為了能直接獲得地球深處高溫高壓條件下之熱傳導率，最近我們已建置雷射加熱技術，並結合DAC與TDTR以實現在高溫高壓下的熱傳導率原位量測。我們將在報告中討論雷射加熱技術的建置，並展示地核金屬於高溫高壓下之熱導率量測結果，及其如何影響地球磁場運作之機制。

實驗室合成鑽石之熱導率與氮雜質含量關係之研究

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摘 要

鑽石作為地球內部重要的高溫高壓礦物，因其獨特的物理特性而受到廣泛關注。其中, 單晶鑽石的高熱傳導率特性 (2000 W/m/K), 被認定是最佳的散熱材料。然而，鑽石的形成過程中無論是天然還是人工，都容易摻入雜質, 其含量對鑽石的物理性質有著顯著的影響。本研究旨在探討合成鑽石(Lab Grown Diamond ,LGD)的熱導率與氮雜質含量之間的關係，以深入了解鑽石材料中雜質對其熱傳導性質的影響。

本研究通過微波電漿化學氣相沉積法 (Microwave Plasma Chemical Vapor Deposition, MPCVD)，製備了一系列含有不同氮雜質含量的單晶鑽石樣品，並結合拉曼光譜與UV-Vis吸收光譜進行氮雜質含量分析。通過時域熱反射(Time-Domain Thermoreflectance, TDTR)測量系統對這些樣品進行系統性的熱導率測量。我們發現鑽石的熱導率與其中氮雜質含量之間存在明顯的相關性：隨著氮雜質含量的增加，鑽石的熱導率呈現出顯著的下降趨勢，這與氮雜質對鑽石晶格結構的影響密切相關。

綜上所述，本研究首次報導實驗室合成鑽石的熱導率與氮雜質含量之間的關係。這不僅有助於我們對鑽石物性的深入理解，也為其在礦物物理及材料科學領域的應用提供重要的參考。

關鍵字:合成單晶鑽石、熱導率、 微波電漿化學氣相沉積法、 時域熱反射量測

Links between sediment consolidation and frictional behaviors at seismic slip rate within the frontal thrust region at the Nankai subduction zone

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Abstract

At subduction zones, rupture propagation is tightly linked to the frictional properties and in situ stress conditions within accreted sediments. However, the effects of sediment consolidation on frictional behaviors at seismic slip rate remain poorly understood. Here we conducted rotary shear friction experiments on clay-rich sediments recovered from the frontal thrust region (Site C0006) at 486 meters below seafloor at the Nankai subduction zone during the International Ocean Discovery Program (IODP) Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) Expedition 316. We remolded and saturated the samples with water, and then presheared the wet gouge at normal stress (σ_n) of 1 MPa and velocity of 1 mm/s. We then increased σ_n step-wisely to achieve the targets ranging from 2 to 18 MPa, before which each individual step was held for 1 hour. Once the target σ_n was reached, we sheared the gouge samples at 1 m/s. The whole experimental progress was performed under fluid drained condition. Our results show that both peak shear strength (τ_{peak}) steady-state strength (τ_{ss}) linearly increase as σ_n increases, with best-fit apparent coefficients of friction of 0.18 and 0.013, respectively. Our SEM observations reveal a random to preferred orientation of platy clays from low to high σ_n, with P shear developed at σ_n of 18 MPa. While deformation mechanisms may change with consolidation as σ_n increases, the apparent friction coefficients remain independent on consolidation, which is contrary to the reported behaviors at lower slip rates (10^{-9} to 10^{-3} m/s). Our experiments performed at seismic slip rate thus may be more appropriate to estimate fracture energy released during rupture propagation.

Anisotropic thermal conductivity of antigorite along slab subduction impacts seismicity of intermediate-depth earthquakes

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Abstract

Double seismic zones (DSZs) are a feature of some subducting slabs, where intermediate-depth earthquakes (~70–300 km) align along two separate planes. The upper seismic plane is generally attributed to dehydration embrittlement, whereas mechanisms forming the lower seismic plane are still debated. Thermal conductivity of slab minerals is expected to control the temperature evolution of subducting slabs, and therefore their seismicity. However, effects of the potential anisotropic thermal conductivity of layered serpentine minerals with crystal preferred orientation on slab's thermal evolution remain poorly understood. Here we measure the lattice thermal conductivity of antigorite, a hydrous serpentine mineral, along its crystallographic *b*- and *c*-axis at relevant high pressure-temperature conditions of subduction. We find that antigorite's thermal conductivity along the *c*-axis is ~3–4 folds smaller than the *b*-axis. Our numerical models further reveal that when the low-thermal-conductivity *c*-axis is aligned normal to the slab dip, antigorite's strongly anisotropic thermal conductivity enables heating at the top portion of the slab, facilitating dehydration embrittlement that causes the seismicity in the upper plane of DSZs. Potentially, the antigorite's thermal insulating effect also hinders the dissipation of frictional heat inside shear zones, promoting thermal runaway along serpentinized faults that could trigger intermediate-depth earthquakes.

龜山島崩塌事件之三維數值模擬

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摘　要

在過去，估算由火山崩塌所引起的海嘯特性通常依賴於對總海嘯體積的近似或使用經驗公式來估算初始波高。在這項研究中，我們以台灣東部外海的龜山島為例，採用不連續雙黏性流模型（Discontinuous Bi-viscous Model，簡稱DBM），並結合了三維不可壓縮流碎波模型Splash3D，來描繪岩屑型山崩引起的地滑動態過程，以及其進入海洋後引發的山崩型海嘯行為。

Huang（2018）利用多波束測深數據、底質剖面、底拖側掃聲納、火花放電波源的震測剖面和遠程操作載具（ROV）潛水數據等資料，研究了龜山島北方海域的地滑特徵。該研究指出，此區地滑堆積物可分為三個MTD（質量運移沉積）單元（MTD1、MTD2和MTD3），主要的火山碎屑崩塌堆積物被識別為MTD3，並提出了一個模型來解釋側翼崩塌及後續的海底山崩事件。

由Huang（2018）對MTD3的測量數據，本研究得以校準DBM中使用的參數，以重建龜山島周邊古代海嘯事件。這不僅有助於更深入了解地滑事件發生期間的動態過程，還為未來該地區潛在海嘯危害的防災參考和制定策略提供了理想的基礎。

Three Dimensional Simulations of Guishan Island Landslide Event

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Abstract

In preceding inquiries, the assessment of tsunami characteristics resulting from landslides has frequently relied on approximations of total tsunami volume or using empirical formulas. This investigation focuses on Guishan Island, situated off the eastern seaboard of Taiwan. Employing a numerical model, specifically the Discontinuous Bi-viscous Model (DBM), we scrutinize the dynamic mechanisms of landslides induced by rockslides and the ensuing behavior of tsunamis engendered by these landslides upon their ingress into the oceanic environment.

This study builds upon the groundwork laid by Huang (2018), who meticulously examined landslide features in the northern maritime vicinity of Guishan Island. Utilizing a combination of sub-bottom profiler data, side-scan sonar imagery, multi-beam bathymetric data, remotely operated vehicle (ROV) dive data, and sparker seismic reflection data, Huang (2018) posited a categorization of the landslide deposits into three distinct Mass Transport Deposit (MTD) units (MTD1, MTD2, and MTD3). The principal avalanche deposits were identified as MTD3, and a conceptual model was proffered to elucidate the lateral collapse and ensuing submarine landslide occurrences.

Leveraging the measurements of MTD3 garnered from Huang's investigation (2018), the present study undertakes the calibration of parameters within the DBM to reconstruct historical tsunami events surrounding Guishan Island. This endeavor not only augments our comprehension of the dynamic processes during landslide incidents but also furnishes a substantive groundwork for disaster mitigation and the formulation of strategies to address potential tsunami perils in the future.

Applications of seismic signal analysis for inferring deep-seated landslide failure mechanisms

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Abstract

This study focused on the Ciland Landslide (CL) caused by rainfall in northeast Taiwan to illustrate how seismic signal analysis revealed the dynamic changes of the CL's failure process enhanced geologists' pre-survey information. According to one-hour spectrograms using a discrete Fourier transform, we identified three distinct events, the first of which was the most substantial. Further examination of spectrograms with a semi-log frequency axis generated by discrete Stockwell transform revealed that the first event consisted of four sliding failures occurring within thirty-seconds, accompanied by a gradual reduction in landslide volume. The second and third events were minor toppling and rockfalls, respectively. This information fixed the primary failure of the sliding behavior and the subsequent failures of an unstable mass presenting toppling and rockfall. Possible CL activity can be addressed by advancing, retrogressing, enlarging, or widening. When we combined this information with field survey results, an imbrication-like feature in the deposits and the gravitational slope deformation of the slope suggested failure mechanisms of enlargement and retrogression of the CL after shear-off from a roadside slope. This study highlights how adjacent seismic stations can offer time vision of the physical processes of landslides, thus aiding geologists in deciphering their mechanisms.

Keywords: Ciland Landslide**,** Spectrograms**,** Discrete Stockwell Transform, Failure Mechanism

新穎即時GNSS解算方法建立及崩塌地應用案例展示

Novel Approach of Real-Time GNSS Landslide Monitoring and its Application

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摘　要

一直以來，如何有效且即時的掌握山崩前兆都是產官學研各界努力的研究發展目標之一，而山崩移動的方式大致可分為兩種，分別是大規模且深度較深(約10m以上)的岩體滑動型態，另一類則為小規模且深度較淺的岩屑崩滑或落石型態，故若能即時觀測地表滑動或變化特徵，對於掌握山崩前兆及發展預警機制將是一大突破。有鑑於此，本研究以嘉義縣中埔鄉T002潛在大規模崩塌地為研究場址，共架設5台GNSS地表觀測站及1台參考站，用以建立適用於即時觀測地表滑動及變化特徵之自動化GNSS解算方法。本研究架設之GNSS觀測站及參考站係採用支援多星系雙頻之瑞士u-blox ZED-F9P高精度晶片所開發之自動化觀測設備。

首先本研究針對解算方法之適地性及最佳化進行探討，採用111年5月至112年12月期間之觀測數據，以15Hz之觀測頻率接收全星系雙頻載波資料，並採移動窗口法調整解算時之時間基線長度，以10分鐘/次之解算頻率進行GNSS資料的靜態差分解算。分析成果顯示，取1小時以上之時間基線長度計算靜態解時，以參考透空圖進行參數優化，並過濾90%信心區間以外之離散值，屬於較適合坡地滑動防災預警之GNSS觀測解算方法。

而於前述觀測期間，恰逢112年8月26日午後之短延時強降雨及112年9月之海葵颱風等2起事件，且均發生坡體滑動行為，透過觀測結果發現，GNSS連續觀測之數據可掌握滑動過程中完整之潛移與變動行為，亦可精準觀察到滑動歷程末段崩塌臨界狀況之加速過程，對於完整的滑動機制與過程之掌控是一大突破，未來若可搭配研究區域內之地震站紀錄，將可準確研判崩塌發生之時間，進一步提供訂定適切之大規模崩塌警戒值，有效提高防災實務規劃之合理性。

關鍵字：大規模崩塌、全球導航系統、地表位移

Keywords: large-scale landslide, Global Navigation Satellite System(GNSS), ground surface displacement

大滅絕下Claviaster libycus的生存策略及其對局部沖刷抑制的貢獻

共同作者[1]、共同作者[1]、共同作者[2]
(1)單位資料、(2)單位資料

摘　要

過去研究指出，歪型海膽起源於侏羅紀早期的正型海膽，生活習性從原本的海底基質之上演化為潛入泥沙中，為了適應潛泥沙的習性，體軸從五輻對稱演化為雙軸對稱。其成功躲過大滅絕事件的能力被歸因於其擁有潛沙的能力，這也成為歪形海膽在新生代繁盛的重要原因之一。在這個背景下，我們提出了一個問題：為何歪型海膽能夠成功存活？是因為牠具備潛沙的能力，還是由於其獨特的外型構造呢？我們的假設是，歪型海膽獨特的外型可能有助於防止底部的沙子被沖走。若這一研究成功，未來或許能將其應用在減少橋墩局部沖刷的工程領域。

為了瞭解歪形海膽在大滅絕中的生存優勢，本研究以隸屬歪型海膽下綱的Claviaster libycus作為研究對象，透過實驗和數值模式，探討其獨特外型所產生的局部沖刷效應。實驗方面，利用水槽執行蓄水深度為0.1公尺的潰壩水流來模擬大滅絕時產生的極端水流。數值模式則是使用Splash3D進行模擬，透過求解Navier-Stokes方程式，結合本研究室開發之非連續雙黏性流模型(Discontinuous Bi-Viscous Model, DBM)，對水體流動和底砂運移之過程進行模擬和分析。

研究結果顯示當Claviaster libycus的生殖孔指向下游時，馬蹄形渦流並不明顯，確實有助於減少局部沖刷的發生。這項發現支持了我們的假設，即Claviaster libycus的特殊形態演化為其在沉積物穩定性和減少局部沖刷中起到積極作用。在探討歪形海膽在大滅絕事件中的生存優勢的基礎上，我們進一步將焦點轉向將其研究成果應用於減少橋墩局部沖刷的可能性，進行單純的圓柱和受到Claviaster libycus保護的圓柱進行了比較，後者的局部沖刷現象確實減輕，說明Claviaster libycus的引入在工程實踐中具有潛在的應用價值。

Analysis of Claviaster Libycus Survival Mechanisms During Mass Extinction and the Impact of Local Scour Problems

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Abstract

Previous research suggests that irregular echinoids evolved from the early Jurassic regularechinoids. Their lifestyle transitioned from residing on the seafloor substrate to burrowing intosediment. In contrast to the five-fold symmetry of regular echinoids, irregular echinoids exhibitbilateral symmetry. The survival capability of irregular echinoids during mass extinction eventsis attributed to their burrowing skills, a crucial factor in their prosperity in the Cenozoic era. Inthis context, a fundamental question arises: What enables the successful survival of irregularechinoids? Is it their burrowing capability or their distinctive morphological features? Ourhypothesis posits that the unique morphology of irregular echinoids may aid in preventing theerosion of sediment from the seafloor. If successful, this study could be applied to mitigate localscour around bridge piers.

This study focuses on Claviaster libycus, a member of the irregular echinoid subclass, tounderstand the survival advantages of irregular echinoids during mass extinctions. Weinvestigate the local scouring effects resulting from its unique morphology through experimentsand numerical modeling. Experimental simulations involve dam-break flows with theimpoundment depth of 0.1 meters to mimic extreme flow conditions during mass extinctionevents. Numerical simulations utilize the Splash3D model, solving the Navier-Stokes equationswith the developed Discontinuous Bi-Viscous Model (DBM) to simulate and analyze waterflow and sediment transport processes.

The research results demonstrate that when the gonopore of Claviaster libycus is directeddownstream, the formation of horseshoe vortices is not prominent, effectively reducing theoccurrence of local scouring. This validates the hypothesis proposed in this study: sea urchinsevolve from pentaradial symmetry, non-burrowing, to bilateral symmetry, burrowing, assistingin stabilizing bottom sediments and reducing the incidence of local scouring. Both cylindricaland square columns exhibit noticeable local scouring, with the square column experiencingparticularly intense scouring depths. Further analysis indicates that the larger water-facing areaof the square column hinders the flow, resulting in strong downward flows and horseshoevortices. To mitigate local scouring around bridge piers, designing piers with streamlinedshapes is recommended. Additionally, the morphological insights from Claviaster libycus havethe potential for application in developing protective devices for bridge piers.

3D Velocity Structure and Geothermal Anomalies Inferred From Asymmetrical Noise-PCC Dataset Collected in ILAN2014 Project

ABSTRACT

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To investigate the seismic characteristics of Ilan Plain, the ILAN2014 experiment deployed 163 temporary stations from August 14, 2014, to January 14, 2015, spaced between 1 to 4 km across the entire area. Our study focuses on seismic ambient noise analysis, which predominantly attributed from primary and secondary microseisms. We calculate the empirical Green's functions (EGFs) of the station pairs by Phase Cross Correlation (PCC) technique. PCC relies on the instantaneous phase information of coherent signals which means, it is sensitive to waveform phase similarity but less sensitive to strong amplitude features (amplitude unbiased). Furthermore, we stacked by time-scale Phase Weighted Stacking (ts-PWS) strategy for signal enhancement and perform the dispersion analysis on group velocity. The group velocity distribution maps reveals the low velocity along the coastline while the mountain side has higher velocity. Ultimately, we use the picked dispersion curve data information to perform the inversion. To invert shear wave velocity structure, the wavelet-based sparsity-constrained method by Fang et al. (2015) were employed. Three different initial model including 1D linearly increased velocity model, average 1D velocity from Huang (2003) and combined velocity of Huang (2003) and Su et al. (2019) were used to reach consitent convergence result. The third approaches provide useful suggestions on the estimated Vs distribution structure features can reach ~2.5 km. The inversion revealed extremely low Vs (Vs < 1.0 km/s) imbedded in the high Vs velocity background at various depths in the south-western part of Ilan Plain that consistent with the known geothermal anomaly sites. Although some station may not provide enough depth solution, however detectable geothermal anomalies are very positive and show fairly distinct features. The exact location and its interpretations may require more careful study and verification.

Keywords: Ambient Noise, Phase Cross Correlation, Phase-weighted Stack, Dispersion Analysis, Surface-wave Inversion, Near-surface Velocity Structure

Can ocean bottom seismometer track the footprints of typhoons? A study of two consecutive super typhoons crossing the northern Ryukyu

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Here, we present a thorough investigation of microseisms generated by two super typhoons, Trami and Kong-Rey, formed in September and October of 2018. Our study is the first of its kind to examine the effects of typhoon-induced microseisms, utilizing data recorded by broadband ocean bottom seismometers (OBSs) which were timely deployed in the northern Ryukyu when the two typhoons passed over these ocean bottom observatories in succession. Our datasets include continuous three-component seismic and hydrophone records from 24 OBSs and 8 land stations along with the wave height (WH) model data from ERA5 and the microseism source excitation model (p2l) data from WAVEWATCH III. We conduct a frequency dependent polarisation analysis to track the source regions of double-frequency (DF) microseisms. Spatiotemporal behaviour is analysed using power spectrum density (PSD) and spectrum analysis. Both super typhoons are dispersive in nature, with their generated microseisms witnessed in both short-period DF (SPDF, 2-6 s) and long-period DF (LPDF, 6-10 s). During the passage of Trami and Kong-Rey near the OBSs between Sept. 28 and Oct. 3, there was a rapid increase in energy, particularly in LPDF with a clear peak revealed in both the bottom pressure and vertical acceleration observed at the OBSs. A significant correlation exists between OBS-recorded pressure energy and sea surface pressure, while ocean wave heights are also remarkably correlated with the vertical PSDs of OBSs. On October 2, interaction between the LPDF microseismic sources of Trami and Kong-Rey resulted in the development of a novel mechanism termed class III, generally formed when a storm swell interferes with another one. On the remaining days, each typhoon's microseismic sources dominated their respective propagations, indicating a class I mechanism which generates microseismic sources following the path of the propagating storm.

Taiwan Real-time Ambient Noise System (TRANS)

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Taiwan, situated in the subtropical region, is surrounded by the ocean and experiences a maritime island climate. It faces a notable natural hazard during summer, with 3 to 4 typhoons on average annually originating from the northwest Pacific region. Additionally, its location at the active convergent plate boundary leads to complex geological structures and frequent seismic activities, resulting in diverse responses to seismic noise across the island. This study develops a system that analyzes continuous ambient noise data from 67 seismic stations across Taiwan in real time. We extract Rayleigh wave signals from ambient noise using the DOP-E method (Berbellini et al., 2019) and calculates back of azimuth, H/V ratios, and seismic velocity variations (dv/v) every 10 min. The system displays both real-time measurements and back-traced historical records (since 2023) to understand the characteristics and potential sources of ambient noise in different frequency bands. By back-projecting obtained back-azimuths at stations, we can trace potential source distribution of Rayleigh waves and observe high spatial correlation with the coastlines and typhoon paths. For Doksuri moderate Typhoon in 2023, we successfully tracked the typhoon's movement from the east to west coast of Taiwan through the Rayleigh waves source mapping. The system will continue operating to monitor and accumulate data for further analysis in the future.

Keywords: Taiwan, seismic noise, Rayleigh waves, typhoon monitoring, back azimuth

Validation of seismic bedload saltation model: From laboratory flume to field-scale experiments

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Abstract

Reliable bedload flux estimations are necessary for a variety of applications such as sedimentation engineering, flood risk mitigation and river restoration. Several seismic physical models with considering different bedload transport mechanisms have been proposed, which provided an opportunity to have quantitative observation in practical. However, a lack of direct measurements of bedload fluxes in field application cause a challenge for the validation of seismic models. In the practical application, the bedload impact kinematics (elasticity and velocity) and particle dynamics assumed in models are crucial for achieving high accuracy in bedload inversion. In-situ seismic parameters such as shear-wave velocity and seismic quality factor are also required to reduce the uncertainty in model prediction. Thus, this study first conducts a series of bedload transport experiments in a flume laboratory to understand the kinematics and mechanics of particle transport by using the smart rock embedded with accelerometer and gyroscope, geophone and hydrophone. Experimental configuration varies with bed flow velocity (0.4~0.7 m/s), flow depth (10~20 cm), and rock density (0.97~1.25 g/cm^3). For the field-scale experiments, we further studied distributed acoustic sensing (DAS) measurement during the experiments, which can record the dynamic strain in fiber optic cable under riverbed. Both case of laboratory flume and field-scale experiments, we will evaluate the performance of the different physical models by comparing in-situ measurements of bedload mass and impact forces recorded by the smart rock. In the case of field experiment, we adopted the active and passive seismic surface wave exploration to investigate the properties of wave propagation and attenuation. The effect of the process of rolling and/or sliding

particles, as opposed to saltating particles, contributing in seismic signal generation, was also explored. Finally, capability for field application is discussed.

Keywords: bedload flux, seismic physical model, flume experiment, distributed acoustic sensing (DAS), smart rock

Enhancing Tsunami Wave Predictions with Ambient Noise Interferometry-derived Empirical Green's Functions

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Abstract

Conventional tsunami wave simulations often rely on accurate bathymetric data for precise waveform fitting, posing challenges in regions with limited bathymetric information. In this study, we present a novel approach utilizing ambient noise interferometry to derive empirical Green's functions (EGFs) from cross-correlation functions (CCFs) extracted from a comprehensive 10-year dataset collected by the Deep-ocean Assessment and Reporting of Tsunami (DART) system in the Pacific Ocean. Our analysis of the CCFs reveals pronounced propagating behavior, indicative of underlying wave dispersion relationships. Particularly, the long-period EGFs exhibit characteristics aligning with shallow water wave dynamics, rendering them suitable for incorporation into tsunami simulations. By circumventing the need for precise bathymetric data, our method offers a practical solution for regions lacking such information. A case study focusing on an Alaska tsunami event demonstrates the efficacy of our EGFs in fitting observed pressure data, showcasing superior performance compared to conventional simulations using the COMCOT model. The fidelity of our simulations underscores the potential of ambient noise interferometry-derived EGFs in enhancing tsunami wave predictions, even in complex coastal environments. Our findings not only contribute to the advancement of tsunami research but also hold significant implications for disaster preparedness and mitigation efforts. By leveraging empirical data and innovative methodologies, we aim to improve the accuracy and reliability of tsunami wave predictions, ultimately enhancing coastal community resilience to these devastating natural phenomena.

Keywords: Tsunami prediction, Ambient noise interferometry, Empirical Green's functions, Cross-correlation functions, Disaster preparedness

Applications in the Passive Monitoring of Ocean Dynamics through the Extraction of Empirical Green's Function from Diffuse Noise

從散射噪音中提取實驗格林函數應用於被動監控海洋動態

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Practical methodologies have been developed for extracting empirical Green's functions from diffuse noise, spanning various scientific disciplines. This study focuses on noise interferometry, utilizing uncontrolled, spatially distributed noise sources for extracting environmental information through cross-correlation of acoustic pressure recorded by hydrophone pairs. The Green's function is empirically estimated from two-point noise cross-correlation functions (NCCFs), serving as a signal to investigate the ocean interior. Detailed and robust environmental information is obtained from each hydrophone pair, employing a time warping transform to separate normal mode components of the NCCF and measure their dispersion curves. The methodology has been applied to data collected in the Straits of Florida and on the continental shelf off New Jersey. Geoacoustic parameters of the seabed are derived from NCCFs, which are evaluated over long averaging times of approximately 1–2 weeks. Similar averaging times are used to characterize sub-seasonal variations in the sound speed profile (SSP) in water. In dynamic environments, these sound speed profiles represent time-averaged values. The results indicate that NCCFs can be reliably retrieved at ranges of 40–70 ocean depths, even with noise averaging times as short as one minute [doi.org/10.1121/10.0023931], suggesting the potential for real-time passive monitoring of ocean dynamics.

Key words: Passive Acoustic Monitoring; Ocean Acoustic Remote Sensing; Noise Interferometry, Time Warping; Geoacoustic Inversion; Sound Speed Profile Tomography; Empirical Green's Functions; Normal Modes; Dispersion Curves.

被動聲學監控；海洋聲學遙測；噪訊干涉，時間扭換；地聲反演；聲層析剖面；實驗格林函數；簡正模；頻散曲線

On the robust relative traveltime measurement of noise-based surface waves across asynchronous networks - application to dense arrays in Taiwan

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Abstract

Ambient noise tomography (ANT), has become a well-established technique for characterizing the structures of the crust and upper mantle. In Taiwan, ANT has significantly improved the lateral resolution of the shallow crust (3-25 km) over the past decade. To further explore near-surface structures, recent efforts involve deploying cost-effective and easily installable geophone nodes and Distributed Acoustic Sensing (DAS), focusing on high-frequency surface waves in small aperture arrays. However, the computational challenges posed by traditional ANT for large-N seismic arrays persist. Additionally, the impact of noise source distribution on long-period surface waves, coupled with measurement precision limitations dictated by the long-wavelength criteria, substantially restricts the capability to investigate deep structures beneath small, dense arrays using noise-based techniques.

This study presents a novel approach employing beamforming to evaluate relative travel time fields for long-period surface waves across three asynchronous dense arrays in Southern Taiwan. The resulting beamforming not only provides valuable insights into the complex nature of wave propagation in Taiwan but also addresses the computational intensity associated with traditional ANT. Leveraging the Eikonal equation, we derive phase velocity maps for multi-mode surface waves from the obtained relative travel time fields.

On Topographic Effect of Surface Wave Tomography: A Case Study in the Ilan area, Northeastern Taiwan

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Abstract

Ambient noise surface wave tomography is widely used nowadays and often assumes great-circle path and ignores the influence of topography, which introduces potential errors in areas with complex velocity structures and topographic variations, such as the Ilan area in NE Taiwan. In this study, we lift these assumptions by incorporating topographic variations into ray tracing scheme for the forward modeling of tomography. We calculate and adjust sensitivity kernels of surface wave dispersion curves along with the elevation and lateral bending of ray paths. This approach allows for one-step inversion possible and achieving a more accurate 3-D velocity model. To validate the method, we carry out numerical waveform simulations with multi-scenario synthetic models in the Ilan area. Synthetic waveforms are generated from sources located in various topographical settings to a dense seismic network covering the plain and mountainous areas. By comparing our predicted surface wave arrival times with those measured on the synthetic waveforms through frequency-time analysis (FTAN), we demonstrate that accounting for topographic variations into ray tracing can significantly improve the accuracy of surface wave travel time predictions, although some challenges remain for short-period data close to 1 sec. Furthermore, our synthetic tests also show that an interstation distance of at least two wavelengths is required to obtain reliable phase velocity measurements on cross-correlation functions. Our study demonstrates that taking into account topographic variations is of importance to achieve higher accuracy/resolution of surface wave tomography when using short-period ambient noise cross-correlation data in a rugged terrain.

墾丁石灰岩洞穴之鹿角化石研究

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摘　要

臺灣南部墾丁森林遊樂區內一處名為龍蝦洞（北緯21° 57’ 55”，東經120° 48’ 46”）的石灰岩洞穴中，發現了許多陸生哺乳動物化石，骨膠碳十四定年的結果顯示此動物群年代為6000年前。2019年，有兩件為帶有部分顱骨的鹿角化石被挖掘出，其中一件保留了近乎完整的左右犄角。鹿犄角常被用於鹿科動物的物種鑑定，此二件標本雖僅具主枝與眉枝，卻保留了典型鹿屬（*Muntiacus*）的特徵。目前臺灣已發表之鹿屬動物化石有左鎮動物群的似步氏鹿（*Muntiacus* cf. *bohlini*）與鹿未定種（*Muntiacus* sp.）、澎湖西嶼的臺灣山羌化石（*Muntiacus reevesi micrurus*）。由於鹿犄角型態與個體差異大，僅憑片段難以辨認物種，過去在龍蝦洞所挖掘到的鹿犄角化石多為不完整之斷角，並無法進行物種鑑定。因此，研究這兩件鹿角化石有助於釐清龍蝦洞的動物群組成與臺灣更新世晚期鹿屬物種的分布狀態。分析的結果顯示此二件標本不屬於臺灣山羌，其形態特徵與北方赤鹿（*Muntiacus vaginalis*）和越南大鹿（*Muntiacus vuquangensis*）最為相似。鹿屬偏好林下灌叢茂密、易於躲避掠食者的環境，鹿屬物種的發現可反映出當時的墾丁地區有較為濃密的灌木叢環境。臺灣現生之鹿屬物種僅臺灣山羌，這二件化石標本為臺灣已滅絕之物種，左鎮的布氏鹿現今也已滅絕，顯示過去臺灣的鹿屬物種多樣性高於現在，但其來源、滅絕原因仍待更進一步的研究。

恆春西臺地北段HC-5和HC-8鑽井岩心微體化石生物地層研究

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摘　要

恆春西臺地出露的地層包括馬鞍山層、恆春石灰岩、四溝層和大平層，其中馬鞍山層一般認為是恆春西臺地的基岩，野外可見少部分露頭出露，恆春石灰岩為不整合於基岩之上年輕地層，在西臺地部分，近期的研究又將其分為蟳廣嘴石灰岩、萬里桐石灰岩和關山石灰岩，這些石灰岩體之間及和四溝層之間相互關係，是上下整合關係，或者是同時異相變化，或是假整合之接觸，不同學者看法仍然分歧。為進一步了解恆春西臺地各石灰岩體的岩相組成、石灰岩厚度、石灰岩的基底產狀和珊瑚礁發育，以及西臺地構造抬升的地質機制，國立自然科學博物館於2015至2018年間陸續在恆春西臺地共鑽取10口岩心，2022年起著手微體化石研究。本報告即是針對HC-5（深度195m）和HC-8（80m）兩口鑽井岩心，從事微體化石的研究，探討其鈣質超微化石和浮游性有孔蟲生物地層，並解讀其岩心的地層年代和構造意義。

HC-5鑽井位在恆春西台地北段的萬佛寺西南側，井口高程157.058m，井深195m，HC-8鑽井位在恆春西台地北段萬佛寺西邊約800公尺的海岸，井口高程8.75m，井深80m。HC-5岩樣超微化石分析結果，在91.6m以上4個標本皆為超微化石NN19a亞帶，時代屬於更新世早期，114.0m以下有4個標本則皆為NN11化石帶，時代屬於中新世晚期，經仔細核對91.6m-114.0m之間岩性差異，認為94.1m處是岩性轉變所在，其上明顯含生物碎屑，往下為含泥質礫岩段，該處未發現有錯動或剪裂現象，馬鞍山層所屬的上新世地層則缺失未鑽遇。HC-8岩樣超微化石分析結果，46.0m以上4個標本為超微化石NN19a亞帶，49.99m-50.965m之間密集採樣3個標本皆為NN11化石帶，時代屬於中新世晚期，54m以下至井底80m之間4個標本的超微化石都稀少，唯井底有一屬於浮游性有孔蟲N22化石帶的標本出現，互相交集結果此岩段超微化石帶應可歸至NN18-NN19s範圍內，時代上也屬於更新世早期，如此則呈現出只有1公尺多的中新世晚期岩段間夾於更新世早期岩層之內，這在地層上極為罕見，判斷可能是在更新世早期岩層堆積之後，其下之中新世晚期沉積物受泥貫入體上擠侵入所造成。

恆春西臺地抬升的地質模式主要分斷層構造和泥貫入體兩種說法，唯直接鑽遇到的證據極少。本報告認為萬佛寺HC-5鑽井在94.1m至井底195m之間已鑽遇中新世晚期的泥貫入體，因井位靠近泥貫入體主體而未鑽穿，形成恆春石灰岩和其下晚中新世礫岩相地層呈似假整合接觸現象。HC-8則推測鑽在泥貫入體邊緣，中新世晚期材料僅薄層少量侵入，成為更新世早期岩層之夾層。因此若恆春西臺地未來的岩心或相關的研究能證實此說法，將更加確認恆春西臺地抬升是受到泥貫入體活動的影響。

關鍵字：恆春西台地、恆春石灰岩、馬鞍山層、鈣質超微化石、鑽井岩心、泥貫入體

Paleoenvironment of the Szekou Formation in West Hengchun Hill: chronostratigraphic constraints from a literature review

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Abstract

The West Hengchun Hill in southernmost Taiwan is renowned for the fossiliferous Szekou Formation, with the recent discovery of an unprecedented well-preserved cetacean fossil in the Tougou area. Although several geological surveys have been done in the past, chronostratigraphic issues continue to hinder our understanding of the paleoenvironment. Over the past few decades, discussions regarding the age of the Szekou Formation have yielded inconsistent results. Due to limitations in dating methods, the youngest estimate is around 30-40 thousand years, while the oldest approaches half a million years. While the age of the Szekou Formation is constrained to the Late Pleistocene, interpretations of its environment remain insufficient.

There also have been various interpretations regarding its stratigraphy. Some scientists indicated a conformal relationship between the Szekou Formation and the underlying Hengchun Limestone, while others proposed a coeval relationship. Therefore, it is difficult to use the contact relationship between strata to assist in solving age problems. Without the ability to further narrow down the age range of the Szekou Formation, it is a challenge to delve deeper into the reasons behind the burial of the cetacean fossils in the Szekou Formation.

This study aims to review previous interpretations, offer new lines of evidence based on new field data, faunal assemblages, and the taphonomy of the cetacean fossils, of the Szekou Formation, and serve as a reference for future studies.

Keywords: Late Pleistocene, Szekou Formation, Hengchun Limestone, taphonomy, microfossil

墾丁石灰岩洞穴之鼬獾化石研究

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摘　要

臺灣南部恆春半島之墾丁地區，擁有分佈廣闊的生物礁石灰岩。其中一處位於國家森林遊樂區內名為「龍蝦洞」的石灰岩洞穴，洞穴內之沉積物中保存大量更新世陸生脊椎動物化石，包含豪豬、家鼠、臺灣刺鼠、高山田鼠、花豹、鼬獾、新竹梅花鹿、羌、獼猴及蹄鼻蝠。其中的鼬獾為此動物群集中少數於現在臺灣依然存在之食肉類物種，本研究採用傳統線性測量及牙齒咬合面之齒尖形態特徵分析，來比較現生鼬獾與化石鼬獾的差異，並加入鼬獾在過去全世界化石紀錄藉以討論墾丁動物群與其他動物群之關聯。同時也藉由最新的骨膠碳十四定年，把本動物群的年代更新為6000年前，而並不足目前較廣泛認定的1萬年以上化石定義，因此在動物群的描述改為亞化石或者動物遺骸或是保留化石的名稱尚待討論。研究分析結果顯示，龍蝦洞出土之鼬獾化石，在牙齒形態特徵上，非常接近現生種鼬獾，在尺寸上落於現生種鼬獾變化範圍內。儘管現生鼬獾在臺灣的分布廣泛數量眾多，然而鼬獾化石的紀錄在全世界卻非常稀少，過去臺灣其他地層及考古遺址中也沒有任何鼬獾的化石紀錄。本研究為鼬獾遷徙來到臺灣的足跡添上一筆重要的資料，鼬獾這類小型食肉類的存在可以反映出墾丁動物群為灌木林及草原環境同時孕育著完整的小型動物生態系有著各類小型脊椎、無脊椎動物來支持鼬獾族群在當時的生存。

關鍵字：恆春、鼬科、食肉目、形態學
Keywords: Hengchun, Mustelidae, Carnivora, morphology

晚更新世的恆春：鯨豚生活與擱淺的熱點？

A possible prehistoric beaching site for whales and dolphins in southern Taiwan

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摘　要

臺灣位處歐亞板塊與菲律賓海板塊聚合地帶，聚合型的板塊邊界造就了臺灣島，雖然形成時間相對年輕，但每年的抬升速率以及伴隨的沉積速率極高，提供上新世－更新世之完整的海相地層紀錄，也因此臺灣西部出土大量上新世－更新世之海相化石，其中體積最大也分布廣泛的，便為鯨豚類的骨骼。

在2022年，國立自然科學博物館團隊於臺灣南端的恆春頭溝地區，發現了一件原位埋藏且保存率超過七成以上的大型鬚鯨化石。根據出土的肋骨與下頜骨尺寸，推估該大型鬚鯨大小超過15公尺長。由於耳骨佚失，因此本研究藉由肩胛骨之形態學研究與多數大型鬚鯨骨骼對比，將該件大型鬚鯨化石歸於灰鯨(*Eschrichtius robustus*)。而因為該件大型鬚鯨化石保存完好，為原位埋藏，埋藏學證據顯示，其應該淺海海岸快速堆積所形成。此外，我們在恆春西台地的不同的層位與不同地點，皆發現了鯨豚化石，說明該區域的鯨豚分布乃是跨時間與跨空間的持續發生之長期現象。

現在，臺灣周邊海域擱淺的鯨豚超過上百隻，且分屬於超過20幾種。而在恆春的歷史上，墾丁南灣也曾為捕鯨船的港口。而化石證據說明，史前時代的恆春為大量鯨豚安眠之地。未來期能透過持續的挖掘與跨領域的合作研究，共同探討恆春西台地這座巨大的鯨魚墓地其背後的地質史與演化史。

恆春西台地頭溝地區四溝層鈣質超微化石生物地層年代再探

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本研究對恆春西台地頭溝地區四溝層的地層樣本進行了鈣質超微化石生物地層的重新檢視，檢視的樣本為科博館 2022 年在恆春頭溝地層中發現的大型鬚鯨類化石之下頜骨所附著的粉砂偏泥樣本 TG-W2。張錫麟和紀文榮 (1983) 在四溝層地層的鈣質超微化石樣本中首先發現了 *Pseudoemiliania lacunosa*，認為四溝層的年代應老於 46 萬年，屬 NN19 鈣質超微化石生物地層帶的上部，但王明惠 (1985) 以高倍率的偏光顯微鏡重新檢視了四溝層樣本的鈣質超微化石，並以指標化石種 *Emiliania huxleyi* 和 *Umbellosphaera tenuis* 的出現，認為前人看到的 *P. lacunosa* 應為老地層來的再積化石，四溝層應屬更年輕的 NN21 下部鈣質超微化石生物地層帶 (268 ~ 85 ka)，但並未明確地定量化 *E. huxleyi* 所佔的比例與生物地層年代的關聯性。本研究為更精確地獲得頭溝鬚鯨類之下頜骨附著地層樣本 TG-W2 的沉積年代，除使用偏光顯微鏡外，並以放大 1-2 萬倍的掃描式電子顯微鏡定量地檢視樣本內的鈣質超微化石種類，辨識出了豐富且保存良好的鈣質超微化石 *E. huxleyi* 和中、小型的 *Gephyrocapsa* 屬，目前已合計辨識出 145 個鈣質超微化石，且並未發現到任何再積化石，顯示此樣本受生物擾動的狀況並不嚴重，顯示樣本年代的高度可信；其關鍵的指標化石種赫氏艾密利鈣板(*E. huxleyi*)佔 15.2%，橋石屬 (*Gephyrocapsa* sp.)共佔 43.5%，對比鄰近的臺灣東部海域加瓜海脊海洋岩芯 ORI-892-GR2-2 之鈣質超微化石豐度結果(Chuang et al., in progress)，判斷恆春頭溝鬚鯨類化石的年代應落在 110 ~ 83 ka 之間，屬海洋氧同位素第五階前段的 5a-5c 區間，古氣候上屬於上次間冰期，並依據樣本內的有孔蟲種類初步分析結果，研判此地古環境為水深五十米左右的半鹽水潟湖環境。

關鍵字：鈣質超微化石、四溝層、*Emiliania huxleyi*、*Gephyrocapsa* sp.

Integration of Machine Learning and Equal Differential Time Method for Enhanced Hypocenter Localization in Earthquake Early Warning Systems

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Abstract

The Earthquake Early Warning System (EEWS) acts as a vital instrument for reducing seismic risks in regions with high seismic vulnerability. A rapid and accurate hypocenter estimation is pivotal for the EEWS, providing the groundwork for more reliable magnitude and intensity assessments necessary for effective earthquake warnings. This study presents an algorithm that integrates machine-learning-based (near) real-time phase picking with an Equal Differential Time (EDT) rapid hypocenter location algorithm, applying it to a 3D velocity model. The phase-picking model, refined through data augmentation, enhances the precision of phase detection in continuous recordings and simultaneous multiple events while ensuring the swift detection of the P-phase, which is critical for early earthquake warnings. Our rapid earthquake location method calculates theoretical P arrivals from potential hypocenters, which are grid points in a 3D velocity model, to stations that are close to their grid points, with the arrivals being stored by station. As P arrivals are detected, the differences in arrival times across stations is utilized in EDT for estimating hypocenters. Furthermore, our earthquake location algorithm is adept at localizing multiple seismic events, a capability that can diminish the risk of unreported cases in scenarios where events occur in close temporal and spatial succession in high seismicity regions. We applied the algorithm to real waveform recordings of recent earthquakes in Taiwan that satisfied the early warning criteria. The results suggest that our algorithm consistently yields more reliable hypocenter estimates compared to those from the currently operational EEWS in Taiwan. Moreover, our algorithm succeeded in locating an earthquake that the current EEWS overlooked due to its failure to recognize P arrivals. These results showcase the potential of our algorithm to provide more accurate hypocenter estimates and to locate earthquake events with complex seismic recordings.

Lithosphere and Asthenosphere Seismic Structure Beneath the Hawaiian Swell from Rayleigh Wave Dispersion

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Abstract

In this study, we re-examine the shear velocity structure in the vicinity of the Hawaiian hotspot and Hawaiian swell using Rayleigh wave data from the PLUME project in the 20-125 s period range. We have approximately 3600 seismograms at 100 s with good signal-to-noise compared to ~ 5200 at 50 s. In the phase velocity inversion with the multiple plane wave technique, we solve simultaneously for azimuthally averaged phase velocities, azimuthal anisotropy, coefficients describing the incoming wavefield, station amplitude corrections and attenuation.

In the 30-70 km depth range, the shear-wave velocity structure is largely featureless with anomalies typically less than +/- 1% from the mean. The lack of features beneath the swell in this depth range shows that the excess elevation is not created by reheating or replacement of the upper lithosphere. At depths shallower than about 70 km, dehydration of the mantle inherited from formation at mid-ocean ridges may make the lithosphere more resistant to tectonic erosion by underlying asthenospheric convection.

At 80-150 km depth, a pronounced region of anomalously low velocities is well-resolved, with average shear velocities varying by as much as 8% from the slow region to the surrounding faster anomalies. The lowest velocities are found beneath the Hawaii-Maui-Molokai part of the island chain, where they reach values ~4.0 km/s. Vertically, the lowest velocities are in the 110-130 km depth range, just beneath the ~100 km vertical extent of cooling beneath normal oceanic lithosphere. This pattern strongly suggests that hot, damp, low-viscosity, buoyant mantle from the plume source spreads out laterally near the top of the pre-existing, low-viscosity channel in the normal oceanic asthenosphere. We demonstrate that the anomalous elevation of the Hawaiian swell is largely explained by the uplift of a 30-km-thick elastic plate from below by this buoyant, low-seismic-velocity layer in the asthenosphere.

利用 SeisComP 軟體建置新一代地震測報系統

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摘　要

SeisComP（Seismological Communication Processor）是一款開源、免費的地震監測軟體。該軟體具備完整的自動化地震資料處理程序，並且提供完善的資料庫連結機制及靈活的資料介接功能。本研究使用 SeisComP 軟體、軟體擴充進階功能 scanloc 及 SeisBench 建置新一代地震測報系統(以下稱本系統)，以強化地震定位效能，目標提升三項地震測報業務，包括：分析即時的地震活動情形、增補歷史地震目錄及取得全球的地震資訊。

有關分析即時的地震活動情形，本研究以 2022 年 3 月 23 日上午 1 時 41 分 ML6.7 花蓮近海地震為例，結果顯示，本系統在主震發生後 1 小時內能提供 66 筆自動定位結果。未來臺灣若發生強震而衍生複雜的餘震序列，本系統有機會能於短時間內掌握即時地震活動情形，進而評估後續的災害風險。至於增補歷史地震目錄，本系統每日可自動化處理臺灣及周遭海域地震活動約 130~140 個地震事件，與人工目錄比對後，大約可解決每日 50~60%的地震數量，有助於加速建置歷史地震目錄。關於全球地震觀測系統，本系統已可產製全球中、大型地震結果，可於未來提供地震速報、海嘯模擬等業務作為地震資訊之參考依據。

本研究已利用 SeisComP 軟體進行上述三項地震測報業務之測試研究，惟震央、深度及規模數據與人工目錄之結果尚有誤差，若未來持續進行系統測試及參數調校，除了可提升中央氣象署地震測報業務效能，還能加值更多的地震資訊，為民眾提供更優質的地震測報服務。

Insights into the Crustal Structures of Southern Taiwan: A Study of Seismic Attenuation Tomography using Amphibious SALUTE Array

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The **S**outhern **A**rray for the **L**ithosphere and **U**plift of **T**aiwan **E**xperiment (SALUTE) is an advanced initiative focused on exploring the structure and dynamics of the crust-mantle system at the subduction-collision transition zone in southern Taiwan and eastern offshore regions. Since October 2021, SALUTE has deployed 31 closely spaced broadband inland stations and 8 broadband ocean bottom seismometers (BBOBSs) to investigate lithospheric complexities resulting from the convergence of the Eurasian plate and Luzon arc. This project utilizes ambient noise and earthquake waveform data to gain unprecedented insights into Taiwan's mountain-building processes and evolution.

This study presents a detailed analysis of *P* and *S* waveforms from regional earthquakes (ML ≥ 3.5) recorded at both inland and ocean bottom broadband stations in southern Taiwan from seismic arrays SALUTE, BATS (Broadband Array in Taiwan for Seismology), and CWASN (Central Weather Administration Seismic Network). Spectral amplitudes of P and S waves within the 1 to 10 Hz frequency band were measured using integrals over wavelet transforms. To accurately account for source structure and geometrical spreading, the spectral amplitudes were calibrated with reference values derived from 1-D synthetic seismograms. The calibrated amplitude spectra were then used to develop a 1-D, frequency-dependent crustal attenuation model, followed by 3-D attenuation tomography. Our findings indicate that high-frequency *P* and *S* attenuation factors exhibit similar decay rates with frequency and are spatially correlated. The tomographic attenuation models reveal consistent lateral variations in coda Q maps. Additionally, the alignment of low Q values with low-velocity sedimentary basins and high Q values with high-velocity metamorphic rocks suggests a significant association between subsurface geology and seismic properties.

Keywords: Frequency-dependent Q, 3-D attenuation tomography, Southern Taiwan, SALUTE

大屯火山地震b值的時空間變化

Spatial and temporal Variations **of seismic b-value at the Tatun Volcano Group, Northern Taiwan**

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摘　要

近年來有許多關於大屯火山的研究，這些研究均指出大屯火山地區的火山地熱活動依舊存在。本研究將針對大屯火山地區，進行地震b值的分析，試圖探討火山地熱活動是否影響當地的地震活動特性。本研究將利用大屯火山觀測站所提供的地震目錄進行分析，這個地震目錄中的地震觀測資料是來自大屯火山地區的40個地震站，其所蒐錄的地震數量十分龐大且完整性高。基於這些地震資料，本研究可探討地震b值隨時間與空間的細緻變化，藉以了解這些變化是否與火山地熱活動相關，與可能的影響範圍。結果顯示，大屯火山地區的地震活動高b值的地區，與火山地熱活動集中的地區相仿，這顯示當地的火山地熱活動可能直接或間接的影響地震活動的b值變化。而從時間上的分析，也發現，大屯火山的b值在2018年前後有明顯的變化。這種系統性的b值變化，暗示孕震的機制可能有所改變。理論上，流體的存在會使規模小的地震更容易發生，其結果就是地震活動的b值呈現偏高的特性（規模與次數的關係式中之斜率）。反之，則是地震活動的b值下降。因此，本研究推測大屯火山淺部的流體分布可能隨著時間而有所變化。

關鍵字：大屯火山, 地震目錄, b 值, 火山地熱活動

Key words: Tatun Volcano Group, seismic catalog, b-value, volcano-hydrothermal activity

Stress fields in the double subduction systems of the Solomon region

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Abstract

The Solomon Islands reside in an intriguing tectonic setting in the southern Pacific for investigating double subduction systems. In the northeastern region, the North Solomon Trench (NST) system was developed by the southward subduction of the Pacific Plate (PA) underneath the Australian-Indian Plate (AI) since the Eocene. As the Ontong-Java Plateau approached the plate boundary, the activity along the NST gradually diminished and the convergence eventually led to a reversal in subduction polarity, shifting the active subduction zone to the San Cristobal Trench (SCT) system in the south. Currently, most seismicity occurs along the SCT and the subducted AI to depths of 200 km at least. Spatial variations in stress are crucial for understanding double subduction systems. Seismic events between 1964 and 2020, with magnitudes (M_w) ranging from 4.5 to 7.0, were analyzed using focal mechanisms derived from a global catalog. These events were clustered based on proximity, and their focal mechanisms were inverted to determine tectonic principal stresses for each cluster. Significant variations in the stress field, including changes in the shape ratio (R) and the maximum horizontal compressive direction (SH_{max}), correspond closely to variations in tectonic regimes. In particular, we identified seismic activity associated with the fading NST system, which is primarily confined under the central Solomon basin to a depth of approximately 150 km, with compressional axes nearly perpendicular to the down-dip direction of the subducted slab. The distinct stress orientations, coupled with reduced seismic activity compared to neighboring SCT events, suggest that seismicity within the older PA slab may be passively induced by interactions with the AI slab at depth.

Revisiting the Initial Peak P-wave Displacement and the Ground Motion Characteristic Period with Signal-to-noise Ratios: A Case Study Using a Low-Cost Sensor Network in Taiwan

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February 5, 2024

On-site earthquake early warning systems can estimate the possible shaking intensity of the earthquake based on the initial P-waves. Researchers have used the following two indicators: the initial peak P-wave displacement (P_d) and the ground motion characteristic period (τ_c). In this study, we re-examine the performance of the two indicators by employing ground motion data from the P-Alert low-cost network in Taiwan. We have found that the signal-to-noise ratio of displacement (SNR_d) is effective for data selection. On the other hand, we have observed the irregular behavior of τ_c in the P-Alert dataset.

Photochemical mechanism to create strong 13C-depletion in CO and carbon cycling in early Mar

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Organic matter found in early Martian sediment may help in defining early Martian environmental conditions and provide the key to understanding Mars' prebiotic chemistry and habitability. However, the origin of this organic matter remains uncertain. Strong 13C depletion was recently discovered in some of this organic matter, and has the potential to elucidate its origins, though a plausible mechanism to cause the strong 13C depletion is unknown. Here, we present experimental and theoretical studies which demonstrated that solar ultraviolet photolysis of CO2 yields strongly 13C-depleted CO. In a reducing atmosphere, CO is converted into organic molecules that are deposited into sediments. Therefore, atmospheric synthesis of organics from CO is a plausible mechanism to explain the presence of organics in early Martian sediments and its strong 13C depletion. Furthermore, this mechanism could explain 13C enrichment of early Martian CO2 without the aid of long-term carbon escape into space. A mass balance model calculation using the estimated isotopic fractionation factor indicated approximately 20% conversion of volcanic CO2 into organics via CO, which agrees with the available data for carbon isotopes. Consequently, our results suggest that considerable amounts of organic matter may have been synthesized from CO in a reducing early Martian atmosphere.

Hf and W partitioning between liquid metal and silicate melt calculated by first principle thermodynamic integration of molecular dynamics and the evolution of ^{182}W isotope of the earth.

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^{182}Hf decays to ^{182}W with a geologically short half-life of approximately 9 m.y. Because Hf and W are lithophile and siderophile elements, respectively, Hf is thought to remain in the silicate melt phase, while W is thought to be distributed in the molten metal in magma ocean. As a result, the initial mantle is considered to have a high μ^{182}W value (deviation from the present-day upper mantle value in ppm) and the metallic core is considered to have a low μ^{182}W. The early mantle-derived rocks such as komatiites have a positive μ^{182}W from +10 to +20 ppm (e.g., Mei et al., 2019). Subsequently, a late veneer with low μ^{182}W is believed to have lowered that of the early mantle to the present-day upper mantle value. The oceanic island basalts originating from the lowermost mantle, such as Hawaii and Samoa, have been reported to show negative μ^{182}W (e.g., Mundl et al., 2017; Rizo et al., 2019).

μ^{182}W variations can be attributed to three main processes. (1) Hf-W fractionation in the mantle. First-principles calculations report that Hf is enriched in bridgmanite; however, the isotopic results are not consistent with the Hf enrichment of bridgmanite subducted into the lower mantle (Deng and Stixrude, 2021). (2) Hf-W fractionation occurred during core formation. (Mundl et al., 2017; Rizo et al., 2017) (3) Extraterrestrial material with low a μ^{182}W fell to the surface by intermittent impact and was incorporated into volcanic rocks and diamictites. To understand the ^{182}W variations in the mantle and its geochemical evolution, it is necessary to focus on the behavior of Hf and W under high pressure and the influence of extraterrestrial materials, such as meteorite impacts.

In this study, we investigated the Hf-W partitioning between silicate melts and molten iron under high-temperature and -pressure conditions using ab initio free energy calculations, which are difficult to achieve in laboratory experiments. We also calculated whether the distribution coefficient changes when iron is mixed with silicate and vice versa. The distribution coefficients of W and Hf were not significantly affected by the addition of Fe to the silicate melt, while the mixing of Fe with O decreased and increased the distribution coefficients of W and Hf, respectively. Importantly, however, in both cases, W and Hf remained siderophile and lithophile, respectively, under the calculated conditions, which is consistent with the model in (2).

Tectonic Evolution

Zircon U-Pb age of metamorphosed welded tuff and Younger Hida granites in the Noto Peninsula, central Japan: Implications on regional Jurassic continental arc magmatism along the eastern margin of the Asian.

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The Noto Peninsula is located on the Japan Sea side of central Japan. On January 1, 2024, a major earthquake of magnitude 7.6 took place at the active fault running along the northern coast of the peninsula. The focal mechanism indicated that the fault moved reversely, uplifting the Noto Peninsula. The Noto Peninsula was a part of the Asian continent before the Miocene opening of the Sea of Japan. It is considered that the faults along the Sea of Japan were normal faults during the opening of the back arc basin. Thus tectonic inversion from normal faults to present reverse fault system controls present geological and topographical features of the peninsula. Most of the areas of the Noto Peninsula are covered by Miocene and Quaternary sediments. However small outcrops of the Mesozoic igneous rocks and gneisses are present as the basement of the Miocene cover sediments. The Mesozoic rocks consist of the Hida Belt, a back arc side unit of the Japanese Islands. It is important to study characteristics of the Mesozoic igneous rocks along the Sea of Japan to compare those of the Asian side for understanding the tectonic evolution of the eastern margin of Asian continents.

In this study, we investigated the geochronology of the metamorphosed welded tuff and granitoids in the Noto Peninsula. Two age groups, 244± 2.6 Ma and 188± 1.6 Ma, were obtained from zircons in the welded tuff. Based on the morphology and internal structure of the zircons, the younger age of 188 Ma is thought to indicate the timing of the formation of welded tuff. The age of the welded tuff is the same as those of the Hida Younger Granites, suggesting that the welded tuff and the Hida Younger Granitoids were formed by the same magmatic activities. The older age of 244 Ma could indicate the age of the source material of the magma providing the welded tuff or the age of host rocks taken in during eruption. The older age of the welded tuff is identical to the age of the Hida Older Granites.

The early Jurassic granitoids are found also in the southern Korean Peninsula. Thus the igneous activities represented by the welded tuff and granitoids of the Hida Belt can be correlated to those of granitoids in the Korean Peninsula. The presence of the welded tuff suggests the subaerial eruption of felsic magma along the eastern margin of the Asian continent. Extensive early Jurassic magmatism along the eastern margin of the Asia continent should supply huge amounts of clastic materials to the trench and must be resulted to form the Jurassic accretionary complex found in East Asia.

Archean lithospheric mantle beneath Proterozoic Central Asia Orogenic Belt

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Abstract

Processes for deriving juvenile material from the mantle and accreting vertically are expected to have affected the subcontinental lithospheric mantle (SCLM) beneath the Central Asia Orogenic Belt (CAOB). In this study, we summarize in-situ Os model ages on sulfides in peridotitic xenoliths from off-cratonic settings (in the basalts from Tariat, Mongolia; Vitim, Khamar Daban Range and Sviyaginsky volcano, Russia) of the CAOB to examine SCLM formation. Mantle xenoliths collected from these volcanic fields are predominantly spinel lherzolites composed of olivines, orthopyroxenes, clinopyroxenes and spinels, with garnet- and spinel-garnet lherzolites only found in Vitim. Geothermal evidence suggests these lherzolites represent residual SCLM, some of which is quite refractory and may be ancient. Most of both their Os T_{MA} from the least-disturbed sulfides ($^{187}Re/^{188}Os<0.07$) and T_{RD} from higher Re/Os sulfides, yield model ages ranging from 0.3 to 3.0 Ga, with peaks around 1.7-1.4, 1.2-0.9 and 0.7-0.5 Ga. These ages suggest that the certain proportions of the SCLM beneath the CAOB region formed at least by the Proterozoic time, and that some domains are Archean. These sulfide Os ages, recording formation of the SCLM and subsequent metasomatism by juvenile crustal-growth events, are consistent with the thermotectonic events recorded in the overlying crust of the ancient microcontinents where the sampled volcanic fields locate. All geochemical characteristics of the Tariat, Vitim, Khamar Daban Range and Sviyaginsky peridotites reveal that ancient, refractory Archean-Proterozoic lithospheric mantle is embedded in the younger, fertile post-Archean lithospheric mantle beneath the CAOB. Comparing the lithospheric mantle domains from the above regions as revealed by Os model ages, with ancient microcontinents at least Mesoproterozoic in age and predating formation of the CAOB significantly diminishes the volume of new juvenile crust generated during the orogeny.

Geochemistry of the middle Triassic felsic magmatism from Kon Tum massif, Central Vietnam

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Key words: slab failure, Kontum massif, Triassic granite, post-collisional granite, central Vietnam

Abstract

The Kontum Massif in central Vietnam is a notable geological formation with a rich history of magmatic and metamorphic processes. It saw the emplacement of granitic plutons during the Late Paleozoic to Early Mesozoic era, linked to the Indosinian orogeny.

In the early to middle Triassic, the Kontum Massif experienced its final phase of granitic magmatism, represented by the Hai Van, Van Canh, and Ba Na complexes. These complexes exhibit high silica (SiO_2= 67.73-80.73 wt.%) and alkali metal content (Na_2O+K_2O= 5.95-9.0 wt.%), and along with relatively low aluminum (Al_2O_3= 10.18-15.58 wt.%) and titanium (TiO_2=0.02-0.56 wt.%) concentrations, characterized by an ASI index ranging from 0.95-1.45, enriched in LREEs with distinct negative Eu anomalies (Eu/Eu*= 0.01-0.16) and low T_{Zr} (~734ºC), T_{SiO2}(~681ºC). Geochemically, they can be divided into (1) collisional-related (229-251 Ma) granites including samples from the Ba Na intrusion and the second phase of the Van Canh complex and (2) post-collisional (224-245 Ma) granites containing the Hai Van complex and the initial phase of the Van Canh complex. The collisional-related group shows characteristics of volcanic arc granites, such as high alkaline and low CaO contents (Na_2O+K_2O = 6.98-8.82 wt.%; CaO = 0.06-2.22 wt.%), elevated FeO^t/MgO ratios (4.88-13.69), and relatively high concentrations of Zr (57.6-441.4 ppm), Ce (19.7-184.4 ppm), and Y (24.9-88.6 ppm). Classified as A2-type suggesting that they were derived by crustal partial melting under relatively low-pressure conditions associated with an orogenic regime. The post-collisional rocks display S-type granite qualities, varying from calcic to alkalic-calcic, with medium to high potassium content and peraluminous composition. They were depleted in Ba, Nb, P, Sr, and Ti, but enriched in Rb, K, Th, U, and Pb. Likely originating from the partial melting of ancient (possibly Paleoproterozoic?) crust, triggered by slab failure during the post-orogenic Indosinian event.

The Saharan Metacraton or Central Saharan Shield?: wither the continental crust of North-Central Africa

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Abstract

The continental crust of North-Central Africa is not well exposed and its formation is poorly understood. Currently, there are two end-member models for the lithotectonic evolution of North-Central Africa. The older hypothesis is that the continental crust between the Arabian-Nubian Shield, West African Craton, and Congo Craton represents an independent craton that was “highly remobilized” during the Late Ediacaran and referred to as the Saharan Metacraton. A recent hypothesis challenges the Saharan Metacraton concept and suggests that the region is a composite or shield terrane of Meso- to Neoproterozoic juvenile terranes and Archean-Paleoproterozoic cratonic nuclei that were sutured along a narrow region that stretches across

Gondwana from Africa to South America. Basement rocks collected from oil exploration drill wells and bedrock exposures across southern Chad reveal distinct Late Ediacaran tectonomagmatic periods. The older period is composed of volcanic-arc granites that extend from the Ouaddaï Massif in the east to the Doba Basin in the southwest and were emplaced at 620–590 Ma. The younger period is composed of post-collisional mafic and silicic plutons throughout south-central Chad (Doba Basin, Ouaddaï Massif, Guéra Massif, Lake Fitri, Lake Iro, Mayo-Kebbi Massif). The volcanic-arc granites were emplaced parallel to the Chad Lineament, a major lithotectonic structure, whereas the post-collisional granites were emplaced on either side of the Chad Lineament. Interestingly, the whole rock Nd isotopes from the volcanic-arc and post-collisional rocks east of the Chad Lineament have $\varepsilon_{Nd}(t)$ values from -14.2 to +0.2 whereas post-collisional rocks west of the Chad Lineament are moderately depleted ($\varepsilon_{Nd}(t)$ = +1.3 to +7.0). The Nd isotopic dichotomy suggests that the continental crust to east of the Chad Lineament is ancient whereas the continental crust to the west is juvenile. Consequently, it is likely that the Chad Lineament represents a suture zone between two distinct lithotectonic domains that collided during the Late Ediacaran and that the crust of North-Central Africa is not a coherent craton.

Response of seismic sources in the reduced micropolar medium

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Abstract

Ground motions resulting from earthquakes pose significant threats to human settlements and economies. Traditionally, structure designs have focused on withstanding horizontal and vertical translational ground movements, overlooking rotational ground motions. This oversight stemmed from the historical belief that earthquake-induced rotational motions were negligible, mainly due to technological limitations in measuring such movements. However, advancements in instrumentation, such as ring laser gyros, fiber optic gyros, and blueSeis-3A, have enabled accurate measurements of rotations, revealing their significant impact on structures.

Discrepancies have been observed between recorded rotations and those analytically calculated using classical elastic theory, commonly employed in modelling Earth media for earthquake effects. These differences suggest that the microstructure of the medium, which is not accounted in classical elasticity theory, may play a significant role in evaluating rotational ground motions induced by earthquakes. The discrepancy between seismic theoretical rotations and experimental data has spurred researchers to develop the reduced micropolar theory in seismology, which incorporates the microstructure of the medium.

We modelled the Earth media using reduced micropolar theory to study the seismic response. The numerical results suggest that these new models excel in accurately simulating rotational ground motions compared to models of classical elastic theory. Unlike the classical model, the reduced micropolar theory introduces two additional material parameters that play a crucial role in determining rotational ground motion. Thus, these models offer a more reliable approach to estimating rotational ground motion induced by earthquakes.

Cluster-Event Method 2 (CEM2), site effects, Vs30, and the geology of the Tohoku region, Japan

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Abstract

Separating source properties and the wave propagation effect has long been a challenge facing seismologists because of the similarities in the waveform spectra that they produce. Well-established approaches involve eliminating the contribution of one of the two effects by taking ratios of the spectra of two events or two stations and then subsequently solving for the other effect. This reduces the amount of data but not the number of parameters. Alternatively, one can formulate a linearized inversion problem with the amount of data exceeding the number of unknowns, resulting in a nominally overdetermined system. However, this method can be highly biased if the site response near the receiver is not considered. Here, we construct a non-linear inversion system by combining the above two approaches based on a previously proposed formulation that partly eliminates the contribution of the source while effectively reducing the parameter-to-data ratio. We can then extract the site effect after the first inversion step. After removing the site effect, the second inversion demonstrates a better determination of the attenuation. In the Tohoku region of Japan, the extracted site effect correlates well with the P-coda spectral ratio, and its characteristics correlate well with the geological setting and the near-surface shear wave velocities. We propose that the site effect develops upon P-wave arrival and amplifies to the coda waves.

Lithospheric Seismic Imaging of Taiwan by Teleseismic Full Waveform Inversion

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The Taiwan orogen is related to the interplay of the Philippine Sea Plate and the Eurasian Plate, consist of the complex structures of subduction transited to collision. Therefore, various orogenic models are proposed that predict different present-day tectonic configurations and heat source distributions. High resolution seismic imaging offers a means to test these evolutionary models. Full Waveform Inversion (FWI) method compares observed and synthetic waveforms to fit reflection and conversion waves generated by the structural interfaces. Unlike classical travel-time tomography, the advantage of FWI requires only a few teleseismic events to better constrain these structures, offering high-resolution imaging from the lithosphere to the upper mantle. In this study, we integrated data from the TAIGER and Formosa Array projects, as well as permanent broadband seismic stations from the CWA, BATS, and NCREE. Only 36 P-wave and 15 S-wave teleseismic events were used for FWI. Frequency bands can be up to a frequency of 0.25 Hz for the final model, providing density, Vp, Vs, and Vp/Vs models with the spatial resolution up to several kilometers. With the newly obtained 3-D models from FWI, we also relocated local events using a nonlinear location method to enhance their spatial accuracy and achieve better constraints on the seismogenic structures.

Toward Real-time Earthquake Occurrence and Site-Specific Ground-Shaking Intensity Forecasting Using ETAS and GMM Techniques

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Abstract

Earthquake forecasting, combined with precise ground-shaking estimations, plays a pivotal role in safeguarding public safety, fortifying infrastructure, and bolstering the preparedness of emergency services. Zhuang (2011) elucidates the methodology for forecasting and simulating earthquake occurrences in Japan utilizing the epidemic-type aftershock sequence (ETAS) model. Based on the ETAS model, this study introduces a comprehensive workflow that integrates ground motion model (GMM) techniques, facilitating accurate short-term forecasting of ground-shaking intensity, which is crucial for effective earthquake warning. At first, an analysis was conducted on an earthquake catalog spanning from 1994 to 2022 to optimize the ETAS parameters. The dataset used in this analysis was comprehensive, allowing for the further calculation of total, background, and clustering seismicity rates for understanding spatiotemporal earthquake occurrence. Subsequently, short-term earthquake activity simulations were performed using these update-to-date seismicity rates to generate synthetic catalogs. The ground-shaking impact on the target sites from each synthetic catalog was assessed by determining the maximum intensity using a selected GMM. This simulation process was repeated to enhance the reliability of the forecasts. Through this process, a probability curve of ground-shaking intensity was created, serving as a robust forecasting at sites of interest. The performance of the forecasting model was demonstrated through an example of the Taitung, Taiwan, earthquake sequence in September 2022, showing its effectiveness in predicting earthquake activity and ground shaking intensity at sites. The proposed forecasting model can quickly deliver short-term seismic hazard curves and warning messages, thereby facilitating timely decision-making.

Joint inversion of seafloor compliance and Rayleigh wave ellipticity for the lithosphere structure in the southwest Okinawa Trough

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Abstract

The eastward opening southwest Okinawa Trough presents a unique opportunity for investigating the evolution of continental rifting. In this study, we employed seafloor compliance measured from 3 Ocean Bottom Seismometers, incorporated with the ellipticity measured from Ambient-noise derived Rayleigh waves, to resolve the 1D velocity structure of the rifting Eurasian lithosphere. Utilizing the Markov-Chain Monte-Carlo method, our inverted models reveal an eastward decrease in shear velocity within the upper crust, and a decrease in shear velocity and compressional/shear velocity ratio is shown in the lower crust and uppermost mantle. These models reconcile the highly faulted upper continental crust in the Okinawa Trough and suggest the presence of a serpentinized uppermost mantle beneath the region.

大陸青海地區中、大規模走向滑移地震之斷層參數研究
Study on the Fault Parameters for the Moderate-to-Large Strike-Slip Earthquakes in Qinghai, China

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摘要

本研究利用週期 100 秒表面波(雷利波及洛夫波)的相速延遲時間來評估大陸青海地區 1997 到 2021 年 $M_W \geq 6.9$ 走向滑移地震的視震源歷時(隨測站方位變化的震源歷時)，並藉此評估這些地震的斷層破裂參數，且進一步探討這些地震的地震矩(M_0)與破裂長度(L)的相關性。透過震源破裂方向性分析得到這些地震有些是單向破裂，一部分是雙向破裂，且破裂長度隨地震矩增加而增加，在 $M_0 > 1\times10^{20}$ Nm，有 $M_0 \propto L$ 的關係；但在 $M_0 < 1\times10^{20}$ Nm，則有 $M_0 \propto L^3$ 的關係。可能的原因是這些地震的破裂寬度(W)差不多，所以對大的 M_0 地震而言，因為 L >> W，導致用 L 在評估M_0就相對重要，因而造成 $M_0 \propto L$；然而對小的 M_0 地震而言，由於 L ≈ W，將導致 L 和 W 在評估 M_0 時就同樣重要，而造成 $M_0 \propto L^3$。

關鍵詞：表面波、視震源歷時、斷層參數、破裂方向性、地震矩

Key Words: surface wave, apparent source duration, fault parameter, rupture directivity, seismic moment

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澎湖活龍灘沙洲地形的時空動態變化 – 2020~2024短時距監測

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摘　要

活龍灘(又稱澎澎灘)為澎湖最年輕的沙洲島，為瞭解此島嶼在不同時空尺度的變化，以及沙洲對於暴浪事件和自然營力的地形反應。在短時間尺度部分，本研究運用多期無人機攝影測量進行短時間尺度的監測，並於颱風和東北季風前實施航測，再將所產製的數值地形模型進行差分數值地形模型（DoD）分析來偵測沙洲變化與侵淤趨勢；另也透過粒徑分析和蒐集相關海氣象環境資料，了解活龍灘變化之自然因素。研究結果顯示，研究期間經歷杜蘇芮颱風、海葵颱風以及小犬颱風，但其沙洲侵淤反應呈現迥然不同的空間趨勢。在杜蘇芮和海葵颱風後，活龍灘主要呈現南岸侵蝕，北岸堆積，此可能受颱風期間東南風為主要風向所影響，且沙尾向北擺動；沉積物粒徑分析的結果則可進一步反應此兩颱風事件對活龍灘的影響範圍。而在小犬颱風侵襲後，活龍灘則呈現南岸堆積，北岸侵蝕的趨勢，此應受颱風過境期間以北風為主要風向，而其沙尾逐漸往南擺動與變化。從零公尺等高線比對的結果，發現活龍灘本島有往西南移動、沙尾往北移動的趨勢。後續將持續進行中長時間尺度的島嶼變化分析。

本研究後續亦將針對活龍灘的形成與不同時間尺度的變化，以及沙洲島對暴浪事件的反應有所瞭解。且能應用於在氣候變遷、極端事件頻仍下，活龍灘上的遊憩區和海鳥保護區的永續發展，這也將有助於管理單位在面對變動環境下的氣候變遷調適能力。

關鍵字:無人機、沙洲、颱風、粒徑分析、氣候變遷

Spatio-Temporal Morphodynamics of Huolongtan Sandbar , Penghu island - Using Short-term Monitoring from 2020 to 2024.

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Abstract

Huolongtan (also known as Pengpengtan) is the youngest sandbar island in Penghu. In order to understand the morphodynamic of this island at different spatial and temporal scales, as well as the geomorphic response of the sandbar to storm events and natural forces. This study used time-series UAS-SfM photogrammetry for short-term scale monitoring, and conducts aerial surveys during typhoons and northeast monsoons. Then we conduced the analysis of DSM of Difference (DoD) to detect sandbar changes and the condition of erosion and aggradation; In addition, through particle size analysis and collection of relevant marine and meteorological environmental data, we can understand the natural factors causing changes in Huolongtan. The research results show that during the study period, Typhoon Dusuri, Typhoon Haikui and Typhoon Xiaogu were experienced, but the sandbank erosion and siltation response showed completely different spatial trends. After typhoons Dusuri and Haikui, Huolongtan mainly showed erosion on the south of sandbar and accumulation on the north part of the sandbar. This may be affected by the southeasterly wind being the main wind direction during the typhoon, and the sand tail swings northward; the results of sediment particle size analysis can be further reflecting the impact of these two typhoons on Huolongtan. After the invasion of Typhoon Xiaogu, Huolongtan showed a tendency of accumulation on the south part of the sandbar and erosion on the north part of the sandbar. This should be due to the fact that the north wind was the main wind direction during the passage of the typhoon, and its sand tail gradually swayed and changed to the south. From the comparison of time-series shoreline extraction, we found that the main island of Huolongtan has a tendency to move to the southwest and the tail of the beach moves to the north. In the future, we will continue to conduct analysis of island changes on medium and long-time scales.

This study will also focus on the formation and changes of Huolongtan at different time scales, as well as the response of Shazhou Island to storm events in the future. It can also be applied to the sustainable development of recreational areas and seabird habitat on Huolongtan under climate change and frequent extreme events. This will also help government authority to the adaption of climate change in the changing environments.

Keywords: UAV, sandbar, typhoon, particle size analysis, climate change

台灣山脈的隆升與侵蝕: 來自山椒魚的啟發

Rapid tectonic uplift but slow erosion of Taiwan's high mountains helps relic Hynobius survive

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摘要

山椒魚(小鯢，Hynobius)屬於兩棲類有尾目(Salamanders)，一種在地球上已存在三億年的物種。山椒魚生存條件嚴苛: 低溫、潮濕、產卵時需清澈水流；但其擅攀爬、躲藏的特性使之能屢屢渡過環境變遷而無恙。已知台灣為全球山椒魚分布的最南界，共分為五種。根據基因學的研究，該五種山椒魚在距今六百萬年前已在東亞產生，之後擴展、進入台灣，各據地盤，並在距今一、兩百萬年前完成進一步的分化。然而，五種山椒魚至今皆面臨生存威脅: 一種已極稀少(阿里山山椒魚；二級保育類動物)，另四種瀕臨滅絕(一級保育類)，且各棲地間多已被深谷分隔。即使如此，幾乎各主要山區都還能尋獲山椒魚的蹤跡: 最北達小烏來(大漢溪)，最南至北大武；最西抵阿里山，最東到太平山。海拔範圍: 雪山山脈 1200 – 3400 m；阿里山、玉山、中央山脈 2000 – 3700 m。居所特性: 足夠土壤、礫石、或倒木(腐葉)供藏身；最愛森林坡地或植被茂密的乾溝，或冰川/冰緣作用留下的碎石坡(> 3000 m)，其中充沛的伏流水為必要條件。

一般視台灣區山椒魚為冰河孑遺物種。然須知，百萬年來山椒魚已經歷多次冰期、間冰期循環——單就此變遷不易解釋其族群由盛轉衰的事實。本研究檢視山椒魚棲地與分布特性，發現除了氣候(溫度)因素，山崩的影響不容忽視。究竟，頻繁的山崩(使坡地、溪溝裸露，破壞伏流水源與水質)，以及其所導致河流快速的堆積或下切，都威脅著山椒魚的生存與擴展。阿里山森林遊樂區是目前山椒魚棲所地形研究最詳細的地點——的確，根據超過 20 筆碳十四定年數據，此間山椒魚所在坡地> 45 ka 以來極為穩定。至此，山椒魚的興衰歷史或暗示: 台灣山脈曾經歷一段地形相對穩定的時期，之後(晚於一、兩百萬年前)河流下切加速，

山崩活動增加，且此一轉變主要發生在中海拔山區，高海拔仍保持相對穩定的狀態。

以上山椒魚所暗示的地形變遷實可與台灣山脈其它地形特徵呼應。首先，台灣山脈廣佈「孑遺」的緩起伏地，一種被陡坡圍繞、殘存於主要稜脊上的低起伏地形。該地形的存在必要經歷河流長時間緩慢的下切(形成緩起伏地)，之後加速(形成陡坡，並侵蝕既有的緩起伏地)。阿里山森林遊樂區即位於一緩起伏地上(碳十四定年資料顯示，環繞該區的陡坡近七千年來進入不穩定的狀態；2009 年甚至發生二萬坪山崩)。相信以上長期、大區域河流下切、山崩潛能的變化乃反映地殼隆升的加速——使山脈整體高度、陡度增加。其次，古山崩研究顯示，高海拔山區坡地乃較中海拔者穩定，雪山山脈地形也較阿里山、玉山、中央山脈者穩定(本研究認為與大地震的分布有關)。以上情景與歷史山崩一致，也與今日山椒魚全島分布的特徵相符。最後，莫忘在地殼快速隆升的背景下，侵蝕相對緩慢的高海拔山區將越來越高，終於在冰期時發育冰川。冰川的發育對山椒魚的影響仍待討論(負面: 山椒魚無法在冰川下生存。正面: 季節性冰川的後退帶來雪水，使冰緣區伏流水不虞匱乏——即使此時氣候相對乾燥)；然可知，融冰後，冰川/冰緣作用留下的碎石坡穩定、伏流水充沛，為山椒魚的生存帶來了契機。

關鍵詞：山椒魚、山崩、河流下切、冰川、台灣山脈。

土砂災害地形製圖之探討

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摘　要

地表形態為地形作用、地質構造、構成地形材料等在特定環境系統中交互作用的結果，對於曾發生過或未來將發生的災害事件，有一定的指標性（井口隆，2015）。臺灣山區常在高強度降雨事件中引發土砂的產出、運移及堆積，形成地景中長期可見或暫時性的特徵地形。若能以良好的視覺化方式，將土砂災害及其相關地形分布研究成果，透過系統性的地形製圖(Geomorphological mapping)，搭配文字說明地形類型、成因、潛在受災風險等資訊，相信可對災害風險評估及防災溝通有所助益。

為探討區域性的土砂災害地形特徵圖的作業模式，本研究設定製圖比例尺為1:25000，以沈淑敏等（2017-2022）的地形特徵圖作業模式為基礎，著重於突顯具再作用(reworking)潛勢之相關地形單元分布及其變動。又設定製圖目標為呈現一地區地形環境特徵、主要地圖使用者為防災規劃工作者和防災教育推廣者兩類。據此，選定高雄市桃源區荖濃溪河段為樣區，涵蓋玉穗溪及布唐布那斯溪等土砂災害重點集水區。透過專家諮詢精進地圖視覺化效果，進行現地訪談以蒐集使用者意見。

相較於前期製圖成果，本研究完成：(1)納入資料定期更新概念，突顯近年發生作用之特徵地形位置；(2)透過歷史影像和多時期數值高程模型的比對，繪製具高變動性而不易長期留存於地景，或受到土砂災害影響之特徵地形；(3)以同一範圍之多時期、多類型插圖組合，結合平面及高程資訊，系統性整合表現地形變化；(4)為促進防災溝通過程之閱讀便利性，設計幫助定位之圖框坐標網格，加強主圖、插圖及說明書之空間對應。若未來可系統性的產出山區各子集水區的地圖，將有助於防災溝通、防災政策討論與制定之參考。

備註：特別感謝國家災害防救科技中心委託辦理計畫「數位地形特徵圖製作」(NCDR-S-112029)對本研究之經費支持，農業部農村發展及水土保持署、經濟部地質調查及礦業管理中心等單位提供相關研究成果及圖資。

台灣巨木棲地分布之地形特性與地質環境

Geomorphological Characteristics and Geological Environment of Giant Tree Habitat Distribution in Taiwan

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國際間巨木常以胸高直徑(Diameter at Breast Height, DBH)或樹高來定義。全球超過 70 m 高的巨木數量稀少(Tng et al., 2012)，分布的地區多在沿海的潮濕地帶或接近赤道無風帶，至今 2022 年全世界前三高的巨木為美國加州的海岸紅木(Sequoia sempervirens)達 115.9m，澳洲塔斯馬尼亞州的山灰(Eucalyptus regnans)達 100.5 m，美國加州的西加雲杉(Picea sitchensis)達 100.2 m，而台灣最高的巨木為台灣杉(Taiwania cryptomerioides)達 84.1 m。台灣的巨木探勘仍處於起始階段，尤其受高山地區地形坡度陡峭、地形變化大等限制，加上以傳統方式測量巨木樹高更為困難，尤其是 65 m 以上的巨木，而隨著現代遙測技術以及攀樹技術的進步，探勘巨木的任務可行性也逐漸提高。2009 年莫拉克風災重創臺灣後，造成地形地貌大幅度改變。災後經濟部中央地質調查所利用空載光達(Airborne LiDAR)技術，進行 6 年(99~104 年)的全臺高解析度數值地形資料建置、地質災害調查及圈繪工作，這也是臺灣首次取得全島高解析度數值地形模型(DEM 及 DSM)，後續內政部 105 年起持續進行國內空載光達地形測製更新成果。在植被茂密的森林區域由於交通不便、地勢陡峭等，其測繪地形的難度較高，以空載光達進行測繪作業時，可同時獲得地表植被與地面回波點雲，有機會獲取樹高訊息，而為有效探索森林中巨木高度的方法。

目前巨木判釋作業以全島光達數值地形資料為基礎，至今 2023 年尋獲最高的巨木為 84.1 m 的台灣杉，全島總共尋獲 941 株巨木，多分布在台灣中高海拔地形區，交通不易抵達而不易於現地地質調查，本研究利用數值地形計量分析與 3 維影像判釋技術，進行每一棵巨木的點位之地質環境分類判釋與統計，初步統計後巨木主要分布在海拔 1,600 千公尺至 2,600 公尺間，分布岩性範圍多為變質砂岩、片岩、千枚岩、和板岩區，分布坡向以西面坡為主，坡面位置多位於坡腹至坡腳範圍，鄰近巨木分布範圍多可發現河川襲奪、坡面重力變形區域、河道堆積和山麓堆積等，前述地形特性與台灣高山造山運動、侵蝕作用息息相關。藉由目前所見能提供巨木長久穩定生長棲地之地形特性，可進一步分析棲地地質環境之可能地質演化模式，了解地質時間尺度的坡地地形變遷對巨木生長的影響，或許可提供台灣地質災害頻繁影響下，相對可找出較安定坡地範圍。

中文關鍵字: 巨木棲地、空載光達、樹冠高度模型、數值地形模型、地形計測
Keywords in English: Giant Tree Habitat, Airborne LiDAR, Canopy Height Model, Geomorphometry

地球系統服務概念應用於礦業資產保存：以九份及金瓜石礦山為例

Integrating the Concept of Geosystem Service into Mining Heritage Conservation: Take the Chiufen and Chinkuashih Mines as the Example

黃家俊

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摘要

具科學與社會價值之礦產業區，其與周邊環境構成之景觀是人類與當地地質密切互動之成果，適合以《文化資產保存法》項下之「文化景觀」進行保存與活化利用，但依當地地質科學重要性指定為「地質公園」亦是可行方式，只是目前國內較少以地質公園保存礦業資產的討論案例。本報告從保育、教育、及地方永續發展三面向，介紹筆者操作地質公園議題以促進九份與金瓜石礦山礦業資產保存的工作歷程。首先，考量地方社群一直以來對礦區居住權益的顧慮，礦業資產保存策略從早期將礦業聚落登錄為文化景觀，轉成從地質保育的角度切入，將聚落之外的重要地質景點指定為地質公園保護核心區作為新方針。再來，透過引用地球系統服務的概念，於博物館展示中將非生物—生物—文化之間的關係串聯起來，強調地質與礦業的不可分性，使重要礦業資產在地質公園框架下也能受到重視。此外，在博物館「礦山學」地方學架構下招募地方社群進行地質公園解說培訓，並於課程中刻意平衡地質、生態與礦業文化議題之比重，試圖促進學員以更全面的視角認識礦山。此策略運用藉由四年期的參與觀察及與地方社群的討論中發現（一）地方社群對地質公園議題之接受度遠高於文化景觀，並期盼地質公園盡早指定成功；(二)地方社群在地質公園框架下，對礦業文史興趣不減，但又提升對地質知識的好奇；(三）透過地質公園強調「由下而上治理」的精神，地方社群能動性提升，甚至主動辦理地質主題課程及安排礦山走讀活動數次。現階段成果說明地質公園雖以保存具科學重要性之地質資產為目標，但透過地球系統服務的論述，亦可整合礦業資產達到保存之效。

臺灣各地諸多礦產業區如北臺灣煤礦產區、出磺坑油氣產區、東臺灣玉石產區等，近年逐漸重視礦業資產保存與活化再利用。本報告提倡透過論述礦產業區的地球系統服務內容，能更全面的保存一地區的礦業資產價值。本報告另呼籲地球系統服務概念因須具備地質基礎知識，是地質工作者跨足文資保存領域的絕佳切入點；同時，透過此概念之跨域整合功能，強調地質知識的社會意義，能使民眾對地質更加重視，有利臺灣地質領域的永續發展。

關鍵字：礦業資產、地質公園、地球系統服務、金瓜石

Key Words: Mining Heritage, Geopark, Geosystem Service, Chinkuashih

以自然紀念物推動地質遺跡保育的機會與挑戰-以臺東八仙洞為例

The chance and challenges of geological heritage conservation by nominating Natural Monument - the case study of Baxian cave, Taitung

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自然紀念物是2016年《文化資產保存法》修正後，新增之項目，旨在保護珍稀礦物以及特殊的地質地形現象，自修法以來國內已有11處地質類的自然紀念物公告。相較於地質遺跡地質敏感區，自然紀念物不僅具有更強的法規強制性，也可以由民間進行提報，然而因為後續有管理維護的權責問題，因此在劃設時須有更周詳的考量。位在臺東縣的八仙洞雖為國定考古遺址，但分布於不同高程的海蝕洞，即具備了自然紀念物指定基準中「特殊地質地形」的條件，因此早在2012年林務局（今林業署）所做的全國地景普查就將八仙洞列為國家級的地景。109年臺東縣政府委託臺灣地質公園學會進行八仙洞自然紀念物價值評估的工作，報告中提出「複合式遺產」的概念希望獲得重視，然而主管機關基於對國定遺址與自然紀念物管理權責區分的疑慮，導致自然紀念物的劃設無法順利推動。從此案例可見，縱使有完整的論述來說明自然紀念物的價值，主管機關的考量仍偏向實務的管理問題，以至於自然紀念物推動的思維，可能要以管理維護可行性高的地點做為優先提報。而主管機關以及大眾對地質保育的觀念較為陌生，未來還需要更多的跨領域合作與公眾推廣來提升國人對地質環境的理解。

關鍵字：地質保育、自然紀念物、地質遺跡、八仙洞、文化資產保存法

Keyword: geoconservation, natural monument, geoheritage, Baxian cave, Cultural Heritage Preservation Act

Sustained Atlantic meltwater drives high sea-level rise rate during ice age terminations

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Abstract

Glacial terminations in the late Pleistocene, marked by significant sea-level rise rates, continue to capture scientific interest. Termination IV (T-IV), occurring approximately 340 thousand years before the present (kyr BP), is particularly noteworthy, showcasing sea-level rise rates exceeding 4 meters per century. Despite its significance, the rapid deglaciation during T-IV remains poorly understood due to limited absolute age constraints on marine records. This study presents radiometrically dated speleothem records, covering the period from 320 to 380 kyr BP, from Bàsura cave in northern Italy. By aligning the speleothem-based chronology with co-registered marine and terrestrial records, we provide valuable insights into the dynamics of T-IV in the North Atlantic and Mediterranean regions. Our findings suggest that the maximum sea-level rise rates during T-IV did not synchronize with major millennial-scale climate shifts, but were linked to the initial phase of the subsequent interglacial period, characterized by abrupt warming in the North Atlantic. By combining our analysis with available data over the past 500 kyr, we propose the crucial role of oceanic feedbacks in driving exceptional rates of sea-level rise during glacial terminations.

Microbial community dynamics in carbon dioxide biomineralization: A Bio-based carbon negative approach for achieving Net Zero-2050

二氧化碳生物礦化過程的微生物群落動態分析：探索實現 2050 年淨零碳排的生物負碳法

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Abstract: Addressing urgent global warming is crucial due to human-induced greenhouse gas emissions, primarily CH_4 and CO_2, causing the greenhouse effect and rising temperatures. The focus on mitigating climate change centers on regulating CO_2 emissions, with elevated carbon capture and storage (CCS) seen as a key solution. This study demonstrates the scope of an advanced bio-based strategy, specifically targeting microbial community dynamics in carbon dioxide biomineralization, aiming to deploy a carbon-negative biotechnology approach for effective carbon capture and storage in surface and deep-subsurface soil, aligning with the Net Zero-2050 initiative. The proposed major steps include categorizing CO_2 sequestration potential, developing a microbial bioproduct, conducting pilot-scale studies for carbon capture via bio-negative carbon conversion technology, and implementing field studies for carbon reduction. The commitment to precision is evident in the meticulous use of physiochemical, mineralogical, and morphological parameters to identify optimal CO_2 storage locations. The use of advanced techniques like the ^{13}C-labeled CO_2 method demonstrates dedication to scientific rigor in quantifying CO_2 sequestration rates. The development of a potent microbial consortium (ureolytic and carbonic anhydrase bacteria) for carbon mineralization shows innovative thinking to enhance

sequestration efficiencies. Assessing practicality through large-scale cultivation of these microbial consortia to establish biogenic $CaCO_3$-based Nano-fertilizers synthesis based sustainable agriculture, bio-grout technology, and carbonic anhydrase enzyme-mediated carbon trapping reflects a pragmatic approach to field deployment challenges. Involving field-scale studies and collaborations with industry and local farmers further demonstrates a commitment to practical solutions and translating scientific advancements into meaningful applications. In conclusion, this research idea presents a holistic and promising initiative that combines scientific excellence with a practical approach to make tangible contributions to carbon sequestration efforts.

Key words: Microbial community 微生物群落, Biomineralization 生物礦化, Carbon capture and storage 碳捕捉及儲存, Negative carbon solution 負碳方案, Net Zero 淨零排放

基於臺灣海峽泥質區岩心重建東亞近千年極端氣候變化

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摘要

臺灣海峽連接東海與南海，接收自鄰近陸地輸出的沉積物，此區域沉積物的搬運與沉降受海流、潮汐、颱風以及洪水等作用影響。該地區易受到颱風等極端氣候事件的影響，造成強風、暴雨和洪水等災害，挾帶大量的陸源沉積物進入臺灣海峽。因此位於東海閩浙泥質區岩心的陸源沉積物之粒徑、元素、黏土礦物、重礦物組成與含量可反映颱風強度及頻率。受限於現今颱風觀測數據時間尺度短，東亞地區颱風強度、頻率與氣候間的變化機制尚未明朗，古颱風及古洪水記錄之精確性與連續性有賴更長時間尺度的古氣候週期紀錄。為研究臺灣海峽區域極端氣候事件，本研究利用馬祖附近海域岩心 ST1 與 ST3 作為研究材料，取底棲有孔蟲 *Ammonia* sp. 進行放射型碳定年，經由 CALIB 軟體將放射性碳同位素年代校正成曆年，自兩支岩心選取共 9 個年代控制點組合得到一個約涵蓋近 1300 年的岩心。本研究採用可見光-近紅外光反射光譜儀（ASD LabSpec Pro FR UV/VIS/NIR spectrometer）分析乾燥研磨後的岩心沉積物表面光譜，並以目標波峰分析法（TPS）與主成分迴歸法（PCR）提取岩心光譜所反映的黏土礦物（伊萊石、高嶺土、膨潤石等）與重礦物（綠簾石）的含量變化。此外，使用手持式

X 射線螢光光譜儀（X-Ray Fluorescence, XRF）檢測分析沉積物元素（鈦、鋯、鋦等）含量變化，並且利用粒徑分析儀分析岩心之粒徑分布，以大於 63 微米的顆粒作為依據，判斷研究區域陸源物質的輸出變化，重建研究區域的颱風、暴雨強度及頻率。研究結果發現自約西元 950 至 1200 年，岩心的鋯/鋦比、重礦物以及黏土礦物的含量皆有上升的趨勢, 代表此時期臺灣與中國可能同時受較強烈的洪水或暴雨影響, 導致臺灣海峽接收到較多的陸源沉積物. 自約西元 1350 至 1500 年岩心的粒徑、鋯/鋦與矽/鋁比的數值相對較低，暗示此時中國及臺灣的氣候可能較為乾燥。而中世紀氣候異常期東亞地區的氣候可能較為暖濕，此時來自於中國的陸源輸出也有明顯的上升；來自臺灣的陸源供應則呈現先降後升。本研究結果顯示，馬祖海域岩心沉積物的粒徑、礦物含量與元素比變化可以反映近 1300 年來強風、暴雨、洪水甚至乾旱等極端氣候事件。透過檢視過去的氣候變化，對

於評估未來區域可能面臨的極端氣候風險將有幫助。

關鍵字: 反射光譜，XRF，黏土礦物，粒徑，極端氣候

以中國吉林泥炭岩心重建 14Kyrs 以來的古氣候和環境突發事件

Climate and environmental changes over the past 14 Kyrs reflected by the peat cores from Hani and Jinchuan peatlands, Jilin, China

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泥炭是由植物死亡後堆積在低窪地的腐殖有機質，泥炭地通常經過由湖泊到沼澤再到泥炭地的發育過程。在泥炭地表層生長的苔蘚、草本和木本植物，死亡後逐漸形成了泥炭記錄。乾燥泥炭含總有機碳（TOC）通常在 20～50%之間，乾密度（DBD-dry bulk density）通常在 0.05～0.4 g/cm^3 之間。由於泥炭岩心的含水率（H_2O%），TOC，DBD 和灰分（ash% at 850 ºC）反映泥炭植被在氣候和水文條件影響下的發育和分解狀況，因此利用這些指標來研究古氣候和環境變化事件。本研究對採自吉林哈尼泥炭地（Bog type）的 8.5 米長的岩心 HNB 和金川泥炭地（Fen type）的 6.5 米長的岩心進行高解析度的 ^{14}C 定年（HNB 有 110 個年齡，JCE 有 53 個年齡），同時用 ^{210}Pb 和 ^{137}Cs 對岩心頂部 30cm 進行定年，得到精準的年代模式。HNB 岩心涵蓋 14100 年記錄，JCE 岩心涵蓋 7080年記錄。對 HNB 岩心每公分採集一個樣本(共 850 個)，對 JCE 岩心上部 0.5 米每公分採集一個樣本，下部 6 米每 2 公分採集一個樣本(共 350 個)。所有樣本進行 H_2O%，TOC，DBD 和 ash%。哈尼泥炭地自 14100 年前開始形成（TOC>20%），在 10160～10090 Cal yr BP 期間有一次強烈的泥沙沖刷事件。這次事件曾被懷疑是火山噴發，但本研究不支持火山噴發說，有可能是水文條件改變造成的。哈尼泥炭地在 13.5～12.5（Younger Dryas），11～10.5，9.5~8.5, 8~5.5, 4~2 Cal yr BP 發育良好（H_2O%和 TOC%高，DBD 和 ash%低），在過去 2 千年內發育波動較大: 2～1.2（Dark age）和 0.6～0.2 Cal yr BP（LIA-2）發育較差; 1.2~0.9 Cal yr BP（MWP）和 0.9～0.6 Cal yr BP（LIA-1）發育較好。距離哈尼泥炭地西北不到 20 公里處的金川泥炭地，從 7080 Cal yr BP 開始發育，在 6800 和 1800 Cal yr BP 各有一期泥炭發育很差的時期，在 5400～4800，4000～2000 和 0.6～0.2 Cal yr BP 發育相對較差。研究表明，不同泥炭地的發育不僅是受氣候的影響，也與水文、礦物質和植被類型有關，需要深入和仔細地研究反映氣候變化的有效指標。

Keywords: ^{14}C dating, ^{210}Pb and ^{137}Cs dating, peat cores in NE China, physical and chemical properties, paleoclimate

The tilting of Eemian sea notches in Phang Nga Bay, peninsular Thailand, reveal tectonic movements over the past 100.000 years

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Erosion of limestone in tropical marine environments can lead to the rapid formation of distinct sea notches marking the position of the average sea level. Fossil sea notches at far-field sites outside the areas directly influenced by glacio-isostatic adjustment processes can therefore be used to infer the position of past global sea-level high-stands.

The Thai-Malay Peninsula is often considered to be tectonically stable on time scales relevant for reconstructing late Quaternary sea level variations. However, here we demonstrate that in Phang-Nga Bay on the western side of the Thai-Malay peninsula, sea notches that formed during the last interglacial about 130-115 ka (Eemian) show a distinct east-west tilt. Clear sea notches, both modern and fossil, can be observed in the Permian Ratburi Limestone that crops out along SSW-NNE trending chains of karst towers in Phang-Nga Bay. Sea notches on the eastern side of the bay are about two meters higher relative to sea notches on the western side of the bay, with sea notches in the middle of the bay having intermediate values.

Because sea notches are erosional features, absolute dating is often difficult. However, oysters found in situ in crevasses in the ceiling of the sea notches have infinite radiocarbon ages, demonstrating that these notches must have formed long before the Holocene sea-level high-stand. Consequently, we conclude that the most likely age of the wide-spread upper sea notches matches the Eemian (MIS 5e) sea level high-stand.

Because the east-west difference in elevation of the Eemian sea notches is roughly perpendicular to the direction of the Khlong Marui strike-slip fault, we postulate that movement along the Khlong Marui fault over the past ca. 100 ky have resulted in about two meters of vertical movement of the landscape. Consequently, on longer time scales, the vertical movements of the Thai-Malay Peninsula must be considered when reconstructing past sea level variations.

台灣地區地動預估式的權重訂定

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摘要

地動預估式(Ground Motion Prediction Equation)的擇定是地震危害分析中的關鍵步驟，過往會將多個預估式透過邏輯樹架構進行綜合分析，以利在程序中考量模型的不確定性，而預估式篩選以及權重分配將是重要的課題。本研究使用1991 年至 2014 年臺灣強地動觀測網所收錄的強震資料，以對數概似函數值(Log-Likelihood, LLH, Scherbaum et al., 2009)與修正歐幾里德距離(Euclidean distance-based ranking, EDR, Akkar and Kale, 2014)兩種方法，客觀評估國內外 16 組地殼地震與隱沒帶地動預估式的匹配度，再藉由 Salic et al. (2017)提出整合計算方式，綜合 LLH 與 EDR 的排序成果，並考量不同自然振動週期下各別模型的表現來決定邏輯樹中的權重。

研究結果顯示，多數模型在 LLH 與 EDR 的排序相近，但仍有部分模型離群，為提升台灣本土地震危害度分析的準確度，本研究篩選更為合適的預估式，再重新計算，訂定邏輯樹中的最終權重，以利進行地震危害度分析時使用。其中，地殼地震類型與隱沒帶地震類型適用性最高的前三組模型分別為 Lin (2009)、Campbell and Bozorgnia (2014)、Chao et al. (2020)與 Phung et al. (2020a)、Lin and Lee (2008)、Chao et al. (2020)。

關鍵詞：地動預估式、邏輯樹、地震危害度分析

Probabilistic Seismic Hazard Assessment of Sumatra, Indonesia

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Abstract

This study assesses probabilistic seismic hazard for Sumatra through a series of progressive approaches. In order to better illustrate possible seismic activity of each seismogenic source—shallow area source, the active fault source, the Sunda trench, and subduction intraslab area source, our analysis implements earthquake catalogs and fault parameters. For the Sumatran fault system (SFS) and the Sunda subduction interface, we assessed their rupture probabilities based on the truncated exponential model, the time-dependent Brownian Passage Time model, and the earthquake rates considering complex multiple-segments rupture. Seismic activity of each area source was modeled through the Gutenberg-Richter law. Due to lack of ground-motion models specifically for the study region, we proposed several earthquake scenarios and compared with instrumental observations and felt report to determine appropriate ground motion models for various sources. We assessed seismic hazard considering the bedrock engineering (i.e., V_s^{30}=760 m/s) and specific site condition (based on the V_s^{30} map by USGS). The results indicate that the region close to the SFS and the Sunda trench face higher hazard levels (1.0-2.1 g) in both 10% and 2% probabilities of exceedance in 50 years. We also assessed city-scale seismic hazard for seven metropolitans, including Lampung, Bengkulu, Bangka Belitung, Palembang, Padang, Medan, and Aceh—through hazard curves and disaggregation. The hazard disaggregation indicated that the SFS is the primary contribution to the overall seismic hazard in the regions. The outcomes of this study provide valuable information for emergency response planning, urban development, and preparedness of governmental agencies before a disastrous earthquake in the Sumatran region.

2022年9月台灣東部地震活動斷層形態構造行為及地震變形分析

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摘　要

台灣位於歐亞板塊與菲律賓海板塊間的活躍造山帶，因此地震活動頻繁，地質災害頻繁，且年收縮率大於8公分。此外，許多發震斷層經過人口稠密地區，造成嚴重破壞。2022年9月，縱谷發生多次特大地震，造成百餘人傷亡，道路、橋樑、房屋受損。但除少數明顯的表面裂痕外，大部分地區斷層的位置、總長度和實際變形情況並不完整。為了更好地約束變形斷層行為和潛在威脅，將重點放在台灣東部的縱谷斷層和中央山脈斷層。為了更好地估計活動斷層周圍的地面變形，地震前後的大面積高解析度地理資訊資料集至關重要。

在本研究中，我們使用 2022 年 4 月和 9 月拍攝的 DMC 航空影像來產生 DTM 和正射影像。基於地震前後的成對正射影像，採用粒子影像測速（PIV）方法計算地面水平變形。斷層附近的垂直位移是根據地震前後差異的數位地形模型（DTM）（DoD）估算的。結果表明，最大水平位移大於2-3公尺，並經現場驗證。

Analysis of active fault morphotectonic behavior and seismic deformation during the September 2022 earthquakes in eastern Taiwan

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Abstract

Taiwan situated on an active orogenic between the Eurasian plate and the Philippine Sea plate with an annual contraction rate of >8 cm, possesses therefore high seismicity and frequent geological hazards. Furthermore, many of the seismogenic faults pass across dense population areas and cause severe damages. In September 2022, several large earthquakes occurred in Longitudinal Valley, caused more than 100 casualties and damage roads, bridges and houses. However, exception of a few apparent surface cracks, the location, total length and actual deformation of the faults remain incomplete in most areas. In order to better constrain deformation and faulting behavior and potential threats, we focus on the Longitudinal Valley fault and Central Range fault in eastern Taiwan. To better estimate ground deformation around the active fault, large-area high-resolution geoinformatic datasets before and after the earthquake are critical. In this study, we use DMC aerial images, taken in April and September 2022, to produce DTM and orthomosaic images. Based on paired orthoimages before and after the earthquake, the particle image velocimetry (PIV) method was used to calculate the horizontal ground deformation. Vertical displacements near the fault were estimated from digital terrain models (DTM) of differences (DoD) pre- and post-earthquake. The results showed that the maximum horizontal displacement was greater than 2-3 meters and was been verified on field

流域集水區山崩與河道土砂生產、運移與災防應用特徵分析

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摘　要

台灣位處板塊交界上，地震密集、構造發達，且位於西北太平洋颱風的路徑上，雨多雨急，故重大土砂等自然災害時有所聞。本研究以南橫荖濃溪為研究目標區，結合地表地質調查，各種已有之遙測影像的運用，透過研究區多時期、高解析、且多樣之空間資料來擷取技術，針對集水區進行各時期地形資料庫建置，用以評估研究區之坡面滑動體活動性、潛在土砂生產，以及河道土砂運移能力變化等土砂變異分析，藉由大面積測繪技術，透過不同時序之地形資訊，合理定量評估集水區尺度之土砂生產、運移及堆積量體時空變化趨勢。汛期前、後精細的數值地形模型資料庫建置，並進行河道內人工結構物對沉積物影響評估，以完整分析評估山崩機制、土砂運移及堆積特性，以及河道清淤等特性，以評估大型山崩對環境造成的衝擊。

本研究建置了2009、2013、2015、2018等年份的地形資料，地形解析度皆在2公尺以內，根據歷年所建置的資料，結果發現河道地區有可見的變化，部分山區的滑動體具有堆積與搬運作用之情形。

Assessment of landslide, Sediment Production and Disaster Prevention in in mountainous watersheds in Taiwan

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Abstract

Since the Chi-Chi earthquake in 1999 and the subsequent Typhoon Morakot in 2009, mass movements such as landslides have become a prominent focus of study. Particularly noteworthy are significant disasters like the Shiaolin Village debris flow and the Yushuishi debris flow in the Southern Cross-Island Highway, which have had a substantial impact on the environment and people's livelihoods. Consequently, the issue of sediment-related disasters has continued to gain attention and expand in recent years. However, estimating the volume of colluvium debris on the slope within the watershed, as well as understanding the transport and deposition of materials in the river channels, poses a challenging issue. This challenge arises from the complexity of geological factors and causes, the prolonged duration of these processes, and the difficulty of implementing engineering solutions. Therefore, effective estimation of the volume, transport, and deposition of sediment, especially in high-risk areas, along with the assessment of potential disaster risks, can be achieved with minimal human resources. This approach can provide effective early warning and reduce the impact of disasters, preventing them before they occur.

The vigorous development of geospatial information technology has not only yielded positive results in land monitoring but has also gradually extended to other application fields. Hazard monitoring is one of its crucial applications. Geospatial information can be obtained through surveying and mapping technology, and through multi-temporal geospatial data, the production, migration, and accumulation of debris deposits can be quantitatively evaluated in a reasonable time and space within the catchment scale.

For these purposes, this study focuses on the Laonongshi catchment, which has experienced past disasters and still retains a substantial amount of residual colluvium on its slopes. This study is dedicated in multi-temporal aerial photogrammetry and dataset generation. By combining surface geological investigations with various existing remote sensing images.Detailed DTMs and Orthomosaic images were established, since pre-Typhoon Morakot in 2009, and post events, including 2009, 2013, 2015, and 2018 with 2 meter resolution. The result reveals significant changes in the river channel and numerous reactivation of landslide debris accumulation.

Internal Waves Simulation by Using the Reduced Gravity Method

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Abstract

Internal waves are waves occurring in stratified fluids and in water, which consists of layers of different densities, recognizable through temperature, salinity, and current fluctuations or via phenomena. Despite their recognition since the early 1900s, capturing internal waves in both spatial and temporal dimensions remains a significant challenge. Numerical modeling has been a crucial tool in simulating the intricate characteristics of internal waves. However, such simulations are often hindered by the inherent complexity of internal wave dynamics, making them both difficult and time-consuming. To address this, the study focused on utilizing the reduced gravity method to simulate internal waves in stratified fluids. This method was anticipated to achieve both speed and accuracy in simulation forecasting.

In this study, the research employed an internal dam break case for calibration and internal solitary waves for validation purposes, utilizing Truchas and COMCOT as numerical modeling tools. The internal dam break case investigated the similarity using the reduced gravity method and non-using reduced gravity methods. In validation, internal solitary waves simulation had been used to compare with analytical results for both used and on-used the methods. All of the simulations were evaluated using the Root-Mean-Square Error (RMSE) to compare between simulations.

The results show that, in the dam break simulation conducted at various resolutions, it was observed that the interface oscillations were nearly identical between the two-layer simulation and the reduced gravity simulation with one layer. Similarly, for the internal solitary wave simulation, there was a remarkable agreement between the analytical and numerical results, with an impressively low RMSE value of 0.000185.

These findings confirm the efficacy of the reduced gravity method in successfully simulating internal waves, facilitating a transition from a two-layer model to a more simplified one-layer model. By employing this method, the research concerning internal waves can be streamlined through expedited simulation. Overall, this study highlights the potential of the reduced gravity method as a valuable tool for the study of internal wave dynamics.

Keywords: CFD, TRUCHAS, COMCOT, internal waves simulation, reduced gravity method.

A numerical study of plunging breakers in the nearshore area under the influence of wind

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Abstract

This study aims to understand the role of wind effects on developing plunging waves in the nearshore region. This study has three types of wind: onshore, offshore, and no wind. The Navier-Stokes Equations coupled with Large Eddy Simulation (LES) were used in this study to simulate and analyze the flow field. The Volume-of-Fluid method (VOF) has been adopted to track the air and water interface. Four numerical simulations involving solitary and regular waves are conducted and show good agreement with the laboratory experiments. After the validation, this study extensively investigates the impact of wind directions and speeds in the laboratory and field scales. Our results reveal that the onshore wind speed increases, breaking waves occur earlier, and their location shifts farther from the coastline. Besides that, higher offshore wind speed delays breaking waves and brings them closer to the coastline. In the absence of wind, waves push the airflow structure forward, accelerating vertical airflow velocity and generating airflow recirculation. Airflow separation and counterclockwise vortex patterns can be observed in onshore and offshore wind conditions. Wind speeds and directions play a crucial role in intensifying airflow vortices. The intensity of airflow vorticity in offshore wind scenarios is stronger than in onshore wind conditions. In addition, it was observed that airflow vortices weaken during breaking processes. Moreover, airflow vortices exhibit greater strength than water vortices during breaking processes. Within the broader context, we present a comprehensive analysis and discussion of the intricate interactions between wind and breaking waves.

Keywords: plunging waves, breaking waves, wind effects, LES, VOF, internal-source wavemaker, sponge layer.

Comparative metagenomic and metabolic profiling of microbialites provides insight into the differentiation of stromatolite and thrombolite during formation in Kenting, Taiwan

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Abstract

Microbialites are organo-sedimentary rocks formed by the interplay between environmental factors and the metabolic activities of microbes, especially cyanobacteria. These partially lithified microbial structures document early Earth environments and life, dating back to at least 3.45 billion years ago. Microbialites are categorized based on their internal textures, with the terms stromatolites, thrombolites, and dendrolites referring to laminated, clotted, and flame-like textures, respectively. The study of the internal structural variations of microbialites and their environmental interactions has been a key research focus. In our field surveys along the Kenting coast, we noted distinct formations of modern stromatolites and thrombolites in proximate locations. This study aims to conduct a comparative analysis of microbial community compositions and predict metabolic functions to uncover the mechanisms behind their differing internal textures. Our analysis, based on 16S rRNA metagenomic data, identified a prevalent presence of Cyanobacteria, Proteobacteria, and Chloroflexi in all mat samples, though their proportions varied between stromatolites and thrombolites. Intriguingly, the microbial compositions of thrombolitic mats were very similar to the first layer of stromatolitic mats. However, unique orders of Cyanobacteria, showcasing diverse coccus and rod cell morphologies in thrombolitic mats, were correlated with the clotted texture typical of thrombolites forming later, whereas filamentous cyanobacteria, Oscillatoriales, were exclusively found in laminated stromatolites. Predictive analyses of metabolic functions suggested that thrombolitic mats contain microbial communities with an enhanced capacity for carbonate accumulation through biomineralization, organo-mineralization, and precipitation processes. These insights provide initial evidence that variations in microbial compositions and functions may explain the differential formation of microbialites.

Spatial variation of stream metabolism in the Kaoping River system

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Abstract

Biological processes, including photosynthesis and respiration, are important mechanisms for atmospheric carbon dioxide (CO_2) regulation. Stream metabolism is considered to play a minor role in global carbon regulation; however, recent research has shown that small mountainous rivers (SMRs) could contribute to an unexpected CO_2 flux into the atmosphere. Given the high flow rate and low nutrient levels typical of mountainous rivers, primary production may be limited, leading to an increase in heterotrophy due to allochthonous production. Still, the rates of gross primary production (GPP) and ecosystem respiration (ER), the understanding of controlling factors on stream metabolisms, and their impact on carbon transfer in SMRs remain limited. This study conducted field measurements of diel changes in dissolved oxygen (DO) concentration, light intensity, and water temperature in the Kaoping River system to estimate the GPP and ER by using the BAyesian Single-station Estimation (BASE) model. We also collected water chemistry data, including nutrients, chlorophyll *a* (chl-*a*), dissolved inorganic carbon, and dissolved organic carbon concentrations during the field monitoring at nine sites in the dry winter season from 2023 to 2024. The metabolism rate shows spatial variation across the river catchment, with ER ranging from 8.6 to 155.6 mg O_2 L^{-1} d^{-1} and GPP ranging from 0.17 to 85.8 mg O_2 L^{-1} d^{-1}. The ER was higher than the GPP in most sites with negative net ecosystem production. Qiwei is the only site with a positive net ecosystem production, where the chl-*a* concentration was the highest among all sites. We will investigate the correlation between water chemistry and stream metabolism to identify controlling factors in the Kaoping River system. Additionally, we will compare our findings with other similar systems.

Keywords: stream metabolism, small mountainous rivers, Kaoping River, BASE model

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A comprehensive study to insight molecular biomineralization of ferromanganese nodules formation as well as its contribution on heavy metals immobilization and nutrient cycling in soil

(土壤鐵錳結核：以微生物視角探索營養物質循環和重金屬封存之礦化作用)

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Abstract

Ferromanganese nodules (FMNs) are concretions of various metallic elements that are typically formed at 40 to 60 cm depths of various iron and manganese-rich soil profiles via biomineralization, which is attributed to the favorable conditions for redox reaction and microbial activity. The biomineralization of FMNs has direct impacts on nutrient cycles and heavy metal (HMs) adsorption of native soil profile. For instance, it was highlighted that the growth of FMNs can retain phosphorus and other HMs such as: lead, copper, zinc, cobalt, and nickel, through redox cycles, acting as a barrier to its movement from land to water bodies and improving soil quality. We hypothesize that the progression of FMNs mineralization in soil is strongly linked to the metabolic activity of specific bacteria, triggered by associated functional genes that lead other metals to become part of FMNs through the microbial immobilization process. Microorganisms interact with geological materials, leading to biomineralization. This process results in the precipitation of metal leachate and the formation of metal oxide coatings, acting as nucleation sites for further mineral formation. This biogenic FMNs formation might induce (biological–chemical) or control (enzymatic) by native microbial process. Herein, the Mn-oxidizer could play a crucial role in FMNs

biomineralization in soil. It has been described that Mn-oxidizing genes in bacteria such as *(mnxG)* in *Bacillus sp., (mofA)* in *Leptothrix discophora sp., (moxA)* in *Pedomicrobium sp., (mopA)* in *Erythrobacter sp., (CumA)* in *Pseudomonas putida and (CotA)* in *Bacillus pumilus* while *Geobacter sp.* carries genes like (*ombB, omaB, OmcB, and ferA), Planctomycetota (mtrC)*, and *Proteobacteria, (cymA)* genes are involves in FMNs formation. Moreover, studying the biomineralization activity of Mn-oxidizer bacteria has high potential to assess their microbial role in forming ferromanganese nodules (FMNs) and trapping other heavy metals in soil systems.

Keywords (關鍵字): Ferromanganese Nodules (鐵錳結核), Nutrient Cycles (養分循環), Heavy Metal Adsorption (重金屬吸附), Bio- Mineralization (生物礦化)

Deciphering the biodegradation potentiality of terrestrial mud volcanoes microbiome for enhanced bioremediation of soil and groundwater ecosystems contaminated with chlorinated volatile organic compounds

泥火山微生物組之生物降解潛力探索—應用於含氯有機化合物汙染的土壤及地下水之生物復育

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Abstract

The bioremediation of soil and groundwater contaminated with chlorinated volatile organic compounds (CVOCs) has gained significant challenges due to the absence of specific micrograms and electron donors in the groundwater ecosystem. Mud volcanoes, which emit substantial amounts of methane, carbon dioxide, and hydrocarbons along with abundant electron acceptors, support diverse microbial ecosystems that exhibit remarkable metabolic versatility and genetic diversity. Therefore, this study explored the mud volcano microbiome and its specific functions associated with the biodegradation of chlorinated volatile organic compounds. The results revealed that most of the samples exhibited reduced ORP ranging from -52 to -170. Full-length 16S rRNA analysis revealed that at the genus level, *Pseudomonas* was the most prevalent CVOCs degrader followed by *Hydrogenophaga* and *Desulfomicrobium* in most of the samples. However, methanotrophic bacteria such as *Methylomicrobium* and *Methylophaga* were only found in MV2-2, MV3-1, and MV4-1 samples. The community

physiological profiling showed that carbohydrates, carboxylic acids, polymers, amines, and phenols were utilized more extensively in the MV4-1 soil followed by MV2-2. Functional analysis revealed that chemoheterotrophy and aerobic chemoheterotrophy were the most prevalent microbial metabolic functions associated with MV1-1 and MV2-1. Similarly, the methane oxidation-related metabolic functions such as methanotrophy, methanol oxidation, and methylotrophy were higher in abundance associated with MV3-1 and MV4-1. Overall the findings of this study highlighted the biodegradation potentiality of mud volcano microbial communities and their metabolic capabilities which could be considered as a potential source of enhanced bioremediation of chlorinated volatile organic compounds.

Keywords: Mud volcanoes 泥火山, microbial community 微生物社群, functional prediction 功能預測, methanotrophs 甲烷代謝, TCE degradation potentiality 三氯乙烯降解潛能

Plant Root-Associated Microbiome-Driven Responses to Heavy Metals and Nutrients Enable Ecological Adaptation of Native Plant Species in Edaphic Serpentine Challenges

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Abstract

Root-associated bacterial communities in serpentine soils play an instrumental role in ecological adaptation, enabling plants to cope with the harsh edaphic challenges, yet our understanding of their role is still in its infancy. Hence, we investigated the root-associated bacterial communities of five plant species prevailing both in serpentine and non-serpentine habitats using high-throughput sequencing coupled with functional and physiological assays. Our results demonstrated that the serpentine site exhibited lower levels of nitrogen (N), phosphorus (P), and potassium (K), but higher concentrations of nickel (Ni), chromium (Cr), cobalt (Co), copper (Cu) and cadmium (Cd) compared to non-serpentine sites. Plant species from serpentine site exhibited significantly higher metal tolerance factor (MTF) values compared to those from non-serpentine site, particularly evident in species like *B. pilosa*, *M. floridulus*, and *L. leucocephala*, underscoring their enhanced resilience to heavy metal accumulation in

serpentine environments. Community-level physiological profiling (CLPP) defined a restricted spectrum of carbon utilization in the higher heavy metal-containing serpentine site plants compared to the non-serpentine site plants. *Zymomonas_mobilis* and *Flavabacterium_sp* exhibited high resistance to heavy metal concentrations and greater adaptability, while, *Staphylococcus_carnosus* showed sensitivity to heavy metals and limited adaptation. Functional predictions revealed a higher enrichment of Ni, Cr, and Co resistance genes in serpentine site plants while genes related to N and P metabolism significantly decreased. *Flavobacterium_sp* showed a strong positive relationship with Cd and Cu, *Zymomonas_mobilis* with Ni, and Cr, *Streptomyces_sp* with Co, and *Staphylococcus_carnosus* with N and P cycling. Redundancy analysis indicated that pH, temperature, MC, and EC were likely the main factors affecting the overall bacterial community compositions, followed by heavy metals.

0403 M_W7.4 花蓮地震序列與地震定位問題

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2024年 4 月3日 7:58分M_W7.4 花蓮地震發生後，揭起了一連串對於此地震構造的討論，斷層傾角向東抑或向西有著不少的爭論，牽扯到基本斷層幾何錯動模式的不同。然而，由於地震速報地震定位、地震目錄甚或運用不同方法重定位有著不小差距。由於台灣地體構造複雜，斷層間彼此距離不若其他區域大，所以稍有不少定位誤差，就會造成對於孕震斷層的誤判，進而產生後續不少不必要的爭議。本研究除了探討過去一些過去地震定位案例的分享，另外，也使用本實驗室發展的SeisBlue深度學習地震定位系統，並即時接收中研院寬頻地震網(BATS)與國研院國家地震工程中心寬頻網(SANTA)，並置入SeisBlue地震監測系統，進行有系統性的地震的偵測與定位，從偵測結果可以清楚判讀地震序列群與相關的地震構造，減少許多孕震構造判讀上的困擾。本研究會探討此地震序列所誘發的不同斷層系統與相對應的斷層機制，其中包括，主震群、最大餘震群與0422壽豐淺層地震群。

Unraveling the rupture source of the 2024 M7.2 Hualien earthquake using geodetic data

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Abstract

The April 3rd M_L 7.2 earthquake struck Hualien, near the junction of the Philippine Sea plate and Yangtze plate, in an area characterized by complex fault systems. Historical earthquakes in this region have revealed various rupture sources. Global Navigation Satellite System (GNSS) observations reveal substantial coseismic deformation across the northern half of Taiwan, with horizontal displacements increasing from 20 mm to 180 mm in western and eastern Taiwan, respectively. Additionally, GNSS horizontal displacements exhibit divergence near Hualien, with northward movements near Xincheng and southward movements near Shoufeng. Coseismic vertical displacement mostly results in uplift from Ciwidian to Xiulin, with the maximum uplift of 442 mm centered at Hualien. Conversely, the Central Range experiences significant subsidence, with the maximum subsidence of 159 mm near Panshi.

Using the Okada half-space model, along with GNSS displacements and InSAR data, we invert for the optimal fault geometry and coseismic slip distribution of the 2024 mainshock. By testing both west-dipping and east-dipping fault planes, we find reasonable fits to the geodetic data. However, the west-dipping fault model yields lower average misfits for GNSS and InSAR data. The inferred fault slip reaches 2-3 m at depths of approximately 20 km, located north of the epicenter. The primary slip zone is beneath Shoufeng and Xincheng, terminating near the transition zone where the inferred orientation of maximum compression changes from NW-SE to NE-SW trending. The inferred coseismic geodetic moment is equivalent to a M_w 7.3 earthquake, consistent with the USGS solution. Furthermore, coseismic uplift compensates for past interseismic subsidence observed over the past 50 years in this region. Continuous investigation of long-term uplift rates from marine terraces, interseismic vertical velocity, and coseismic uplift during recent earthquakes in eastern Taiwan is crucial for revealing earthquake cycle deformation over a longer time history.

2024 年花蓮地震後的海岸抬升與波浪事件初步調查

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2024 年規模 7.4 的花蓮地震於花蓮市沿海到鹽寮海岸一帶產生了數十公分不等的同震海岸抬升現象。其中，又以米崙台地東側海岸至花蓮市北濱公園一帶最為明顯。透過震後野外調查與遙測影像分析，我們發現花蓮港至北濱一帶皆可觀察到約 30 到 40 公分的海岸抬升，且此明確的海岸抬升現象可往南延伸至花蓮溪口以南，並於鹽寮海岸一帶仍可觀察到約 10 到 20 公分左右的地體抬升。綜合花蓮港區與海岸山脈靠海側的震後觀察，我們的初步調查成果顯示此一抬升現象自花蓮港北方開始由北往南逐步遞減，並約略止於磯崎以北。此一初步調查成果與 GNSS 衛星大地測量結果，以及合成孔徑雷達衛星干涉分析成果相若，顯示花蓮地震主要的地表變形帶應集中於海岸與外海地區，而縱谷斷層與米崙斷層沿線則無淺部之地表變形與破裂發生。除了明顯的同震抬升之外，本研究於花蓮溪口至磯崎一帶海岸亦觀察到疑似為花蓮地震海嘯波浸淹之痕跡，顯示該日的最大海嘯波可能於該區形成約 2 公尺左右的海嘯浸淹高度。

關鍵字：2024 花蓮地震、同震變形

Keywords : 2024 Hualien earthquake, Coseismic coastal uplift

A conjugated structure discloses interaction between two fault systems in eastern Taiwan during 2022 Guangfu earthquake

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Abstract

The Longitudinal Valley (LV) in the eastern Taiwan is located at the convergent boundary between the Philippine Sea Plate and the Eurasian Plate. Within the LV, two significant fault systems, the Longitudinal Valley Fault (LVF) in the eastern part and the Central Range Fault (CeRF) in the western part, have been recognized. However, understanding the precise mechanisms and spatial relationships of the two fault systems in the middle segment of the LV has remained a challenge. In this study, we integrate various data sources, including geodetic measurements, seismic data, field investigations, and simulation results, all obtained during the 2022 Guangfu earthquake event. Our goal is to shed light on the complex structural interactions between the two fault systems. We introduce a coupled structural model consisting of a main fault plane and a coupled ramp plane. The deep-seated fault plane is constrained using seismic data, while the shallow ramp plane is determined through field investigations. Geodetic measurements are utilized to constrain the surface deformation resulting from dislocation model. The simulation outcomes reveal that the 2022 Guangfu earthquake was primarily triggered by the activity along the CeRF. The CeRF experienced an eastward reverse slip of approximately 58 cm along the fault plane. This fault not only intersects the LVF beneath the Coastal Range but also initiates the development of a ramp plane along pre-existing fault planes of the LVF. This intricate interplay results in approximately 20 cm of vertical surface deformation within the Coastal Range. The linear connection observed in the simulation residuals is associated with pre-existing faults within the LVF system. This alignment corresponds to the ground

distribution of ramp plane, suggesting that older fault systems within this area exhibit characteristics of reactivation in response to earthquake-induced processes. Our study not only pinpoints the potential location of the CeRF intersecting with the LVF in the middle segment of the LV but also provides insight into one of the interaction mechanisms between the CeRF and the LVF. These findings hold significant implications for assessing seismogenic structural activity and enhancing the mitigation of regional earthquake hazards in the future.

Keyword: InSAR, GNSS, dislocation model, conjugated structure, 2022 Guangfu earthquake

Rethinking researches on seismic hazard mitigation after the 2024 Hualien, Taiwan, earthquake sequence

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Abstract

This study validates seismic hazard mitigation strategies applied to the 2024 M_w7.5 Hualien earthquake and its sequence.

Before a devastating earthquake, a probabilistic seismic hazard assessment is crucial to quantify the impact of earthquakes. Given the complex rupture behavior of the Hualien earthquake, it is challenging to evaluate seismic hazards using a simplistic seismic model. Therefore, this study adopted the Seismic Hazard and Earthquake Rates In Fault Systems (SHERIFS) model, which allows for the possibility of multiple-structure ruptures, to forecast the potential for larger seismic events than those typically characterized. For instance, an earthquake with magnitudes ranging from 7.5 to 7.7 could be expected to occur during a multi-fault rupture in the northern Longitudinal Valley. This assumption aligns with the events of the 1951 sequence, which began with an ML7.3 earthquake on the Longitudinal Valley fault, and suggests the potential for the occurrence of the 2024 M_w7.5 Hualien earthquake.

To reduce seismic risk during the coseismic period, this study developed an earthquake early warning (EEW) system based on the Transformer Earthquake Alerting Model (TEAM), which was optimized using seismic data from Taiwan. When retroactively applied to the 2024 Hualien earthquake, the system predicted an Intensity greater than 4 across most of central and northern Taiwan within 7 seconds of the first p-wave arrival at the initial station. This optimization improves the model's effectiveness in Taiwan's earthquake early warning system by providing longer warning times and generating more accurate intensity maps.

After occurrence of a significant earthquake, it is crucial to clarify the frequency of aftershocks and possibility of another larger earthquake. Thus, earthquake forecasting plays a pivotal role in safeguarding public safety, fortifying infrastructure, and bolstering the preparedness of emergency services. This study introduces a comprehensive workflow that integrates the ETAS model to facilitate short-term earthquake forecasting. The application of this system to the 2024 Hualien sequence demonstrates its effectiveness in forecasting the spatial-temporal distribution of earthquake activity.

The application of these mitigation strategies to the 2024 Hualien earthquake has confirmed their effectiveness in enhancing safety and reducing seismic risks before, during, and after significant seismic events.

關鍵字：花蓮地震、地震危害分析、地震預警、地震預報

Keywords: Hualien earthquake, probabilistic seismic hazard assessment, earthquake early warning, earthquake forecasting

2024 年 4 月 3 日地震前後礁溪溫泉監測井水位變化

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摘要

2024 年 4 月 3 日 7:58 發生規模 7.2 的強震，震央位於花蓮外海(北緯 23.77 度、東經 121.66 度)，震源深度約 15.5 公里。本研究分析該地震前後礁溪溫泉 11 口監測井的水位變化，各監測井相鄰距離約 200~300 公尺、井深 45~145 公尺，擷取 4 月 3 日 7:50 的水位讀值以及 7:50 之後一小時內最高或最低的水位讀值，結果發現有 2 口監測井(公園路和碧富邑)的水位下降，其餘 9 口監測井的水位上升，其中遊客中心監測井的水位上升最大，約 1.62 公尺，公園路監測井的水位下降最大，約 0.38 公尺。遊客中心監測井可能位在一個局部的凹陷區，所以水位上升最明顯，公園路監測井井底已進入基盤，其水位可能跟局部的張裂有關。水位不管是上升或下降，目前都維持原水位或持續上升中，其中遊客中心、香檳、公園、皇泰、奇立丹和礁溪鄉公所監測井水位在地震過後，有跳升現象，未降回原來的水位水平，整體來說，整個礁溪溫泉的水位在地震前並無異常的變化，但在地震過後水位有明顯的上升現象。

關鍵詞：礁溪溫泉、花蓮地震、同震水位

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2024 M_L 7.2 地震前後一個月的全台灣地震活動分析：基於機器學習地震目錄的觀察

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摘要

台灣時間 2024 年 4 月 3 日早上 7:58 分，規模 7.2 的地震發生於花蓮近海，在斷層帶上亦陸陸續續發生了多起規模 6 以上的地震。此外，在該地震發生前幾天，嘉義地區亦有多起規模 3 以上的地震活動。本研究使用氣象署以及台灣寬頻地震網所提供總計約 635 個測站，1 個月的連續資料，對全台灣及周遭的地震活動進行分析。本研究使用基於深度學習挑波模型 RED-PAN 於各測站搜尋地震之訊號，並使用 back-projection 演算法連結波相(phase association)，再使用三維速度模型進行絕對定位及相對定位，觀察孕震構造的地震活動以及潛在的幾何形貌。基於本研究的目錄顯示，主震座落的斷層帶擁有複雜的斷層系統，包含了不同深度，不同傾向的構造。並且餘震在時空間上的分布並不連續，其分佈並非從主震位置往北延伸，而是短時間內在斷層帶內不同深度大量發生。

除了地震活動分析之外，本研究亦談討基於不同波相連結方法的全自動化地震目錄製作流程的品質以及應用的時效性，即 back-projection 及 PyOcto，前者產製的地震目錄品質最為可靠，而後者演算速度可達到近即時(數分鐘)。然而，PyOcto 雖然可在近即時的狀態下快速產出餘震分佈，其存在一定比例的連結失誤事件。因此近即時全自動化地震目錄的發報準則，包括如何考量時效性及正確性，仍有相當大的討論空間。

關鍵字: 機器學習, 2024/04/03 花蓮地震序列, 嘉義地震

0403花蓮地震之海嘯訊號解析與模擬分析

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摘　要

本研究探討了2023年發生在台灣東部近海的0403花蓮地震所引發的海嘯事件。該地震事件震央位在花蓮東方外海，規模為近25年來規模最大，為台灣東部沿岸地區帶來將近1公尺的海嘯。研究中採用康乃爾大學開發的COMCOT多重網格海嘯模型，模擬海嘯的傳播及其對沿海之影響。

地震學者們表示，該地震事件從震源機制分析是屬於逆衝斷層，但由於對海域孕震構造理解有限，本次地震事件屬於西傾或東傾逆衝斷層，還需要更多佐證加以判斷。因此本研究於海嘯模擬中，蒐集了多個震源機制解，包括來自USGS、TESIS、GCMT和GEOCSOPE的解，以及透過逆推法獲得的多個有限斷層解並比較不同海嘯源設置下模擬水位的變化情形。為驗證模擬結果，研究將模擬的海嘯波形與多個來源的觀測資料進行了比較，包括國內中央氣象署台灣沿岸潮位站及海纜觀測系統，以及國外NDBC的DART浮標資料、UNESCO提供的琉球群島水位資料等。

對比分析顯示，在同一來源的斷層機制解下，使用西傾斷層面的模擬更好地重現了潮位站記錄到的海嘯波形，優於採用東傾斷層面的模擬結果。

關鍵字：0403花蓮地震、海嘯、COMCOT

Seismo-tectonic structures of Eastern Taiwan: insights from numerical thermo-mechanical models of arc-continent collision

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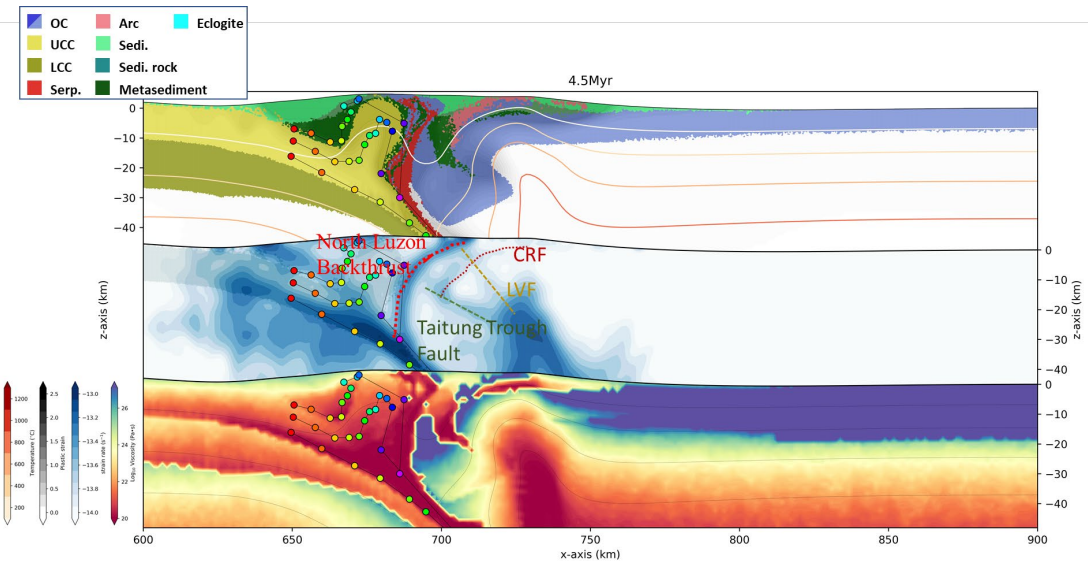
Abstract

The 0403 Hualien earthquake and subsequent aftershocks revealed a complex fault network in Eastern Taiwan. This study employs 2D numerical thermo-mechanical models to simulate the arc-continent collision and elucidate the fault geometries in this region. The time progression of the model can be understood as the structure evolution from south to north. Following the subduction initiation at the Manila Trench, the oceanic crust of the South China Sea (SCS) is subducted eastward under the Philippian Sea plate, leading to the formation of the Luzon Arc (LA). As the SCS transition crust, which resists deep subduction due to its buoyancy, approaches the trench, it causes horizontal shortening to be transferred to the upper plate. Subsequent deformation results in the buckling of the forearc basin into a syncline and the formation of the east-dipping Taitung Trough fault, which facilitates overthrusting of the LA over the basin sediment and its basement. At the surface, this fault converges with the North Luzon Backthrust to form an inverted-V shape in cross-sectional depth views, burying forearc basement and basin sediments at depths of 20-40 km. As the collision progresses, the North Luzon Backthrust's dip becomes nearly vertical below 10 km, while the Taitung Trough fault sinks to 15 km depth, coinciding with the emergence of the Longitudinal Valley fault (LVF). A new backthrust develops parallel to the North Luzon Backthrust but further east, matching the observed Central Range fault (CRF) and extending shallowly eastward towards the Coastal Range, possibly aligning with the Chimei Canyon thrust. This evolution results in a complex #-shaped fault system beneath the Longitudinal Valley, profoundly affecting the region's seismotectonic structure. The correlation of shear zones in the model with the aftershock distribution validates our forward model's accuracy in capturing the essential tectonic blocks.



利用碎屑鋯石分析探討台灣西南海域地層年代與物源演化

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摘　要

隨著碎屑鋯石定年分析技術日漸成熟，其成為探討沉積物源與演化、最大沉積年代的工具之一，在油氣探勘上，亦可協助進行盆地演化的探討。本研究選取台灣西南海域井下 11 個先中新統樣本，及 10 個新近系樣本，將其劃分成西部次盆地、F 構造、E 區塊、澎湖盆地四個區域，進行碎屑鋯石鈾-鉛定年分析，同時對比其他鄰近地區如：珠江口盆地、澎湖、台灣淺灘等地之碎屑鋯石年代頻譜紀錄，以探討台灣西南海域確切地層年代，並了解沉積物源演化過程。透過樣本中最年輕鋯石年代(MDA)、碎屑鋯石頻譜紀錄等，建議可能的地層年代，其結果大致與鑽井報告建議之年代一致，唯有 M-1、S-2、D-1、J-1、K-1 井中的 7 個樣本之年代有進行細微調整；此外，也發現由中生界至新近系，台灣及其他沉積盆地碎屑鋯石頻譜峰值有所變化，從以年輕燕山、印支期為主，轉為較為複雜頻譜(年輕碎屑鋯石減少)，唯 T-1 井始新統樣本，碎屑鋯石年代頻譜複雜，顯示其沉積環境可能較為特殊，且可能受控於斷層活動。

另外，根據多維尺度化分析、離析分析結果，顯示早中新世以來，中生代高區之沉積物源供應減少，河流則逐漸增加；而自上新世之後，由於弧-陸碰撞，台灣島形成，沉積物主要多來自台灣。

關鍵字：碎屑鋯石、沉積物源、最大沉積年代

Zircon and monazite petrochronology of a high-pressure felsic gneiss discovered from the Kontum Massif, central Vietnam

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Petrochronology is a method that combines *in-situ* dating using chronometers such as zircon and monazite with metamorphic reactions, partial melting, and *P-T* history. Here, we show the effectiveness of this method through its application to a continental collision zone. The central to northern parts of Vietnam is considered to have formed by collision between the Indochina block and the South China block during the Late Permian to the Middle Triassic. We have recently discovered a high-pressure felsic gneiss from the eastern part of the Ngoc Linh complex in the Kontum Massif, which was previously regarded as an amphibolite facies (up to ~5 kbar and ~700 °C) terrain. The *P-T* pseudosection combined with Zr-in-rutile thermometry shows that peak *P-T* conditions were ~12 kbar and ~810 °C. Zircon and monazite in this high-pressure gneiss were dated by *in-situ* U-Pb technique with a LA-ICPMS at the Institute of Earth sciences, Academia Sinica. The zircon grains display developed radial sector zoning or fir-tree sector zoning, consistent with formation by high-grade metamorphism. The average $^{206}Pb/^{238}U$ age for zircon is 253.0±1.7 Ma (n=33). Monazite inclusions in garnet have a lower intercept age of 252.8±1.9 Ma (n=12) that compared closely to the zircon age, which indicate the timing of the peak metamorphism. Monazite in the matrix commonly shows a high-Y and low-Th/U core surrounded by a low-Y and high-Th/U rim. The lower intercept ages of the core and most rim are overlapped each other, giving the 257.1±1.9 Ma (n=14) and 258.4±1.7 Ma (n=20), respectively. These ages indicate the timing of prograde metamorphism. Thus, metamorphism occurred over a 4-5 Myr timescale. The results firstly revealed that the Permian-Triassic continental collision affected the eastern part of Ngoc Linh Complex, where a continental crust was subducted to its maximum depth (~45 km) in a short period of time from 258 Ma to 253 Ma.

整合地球科學教育:以數位攝影測量建立校園東華大學 3D 模型

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摘 要

傳統地球科學教育中利用遙測方式擷取地表資訊包括地表地形、岩石/構造分布、土地利用型態與植生分布等，以往這些遙測資訊掌握在許多個不同機構中獲取極為困難，使用這些資料也需要不同的知識與訓練，但過去 10 年以來利用無人機搭載可見光相機、多/高光譜相機、RTK-GPS 與光達系統，使這些資料獲取可以由單一或少數單位獲得，所以利用這些資料時整合型知識背景的訓練變成非常重要。但單一的遙測課程無法提供包括攝影測量、全球衛星定位系統、遙測資料處理、光達與雷達遙測等全方位資訊，造成資料容易獲得但解釋可能發生困難的落差。

本研究利用遙測中最常用的數位攝影測量方法，建立校園東華大學 3D 模型，資料來源是自然資源與環境學系碩士班攝影測量課程一學期三學分課程的課堂練習，背景知識包括無人機搭載可見光/多光譜相機、RTK-GPS 測量與遙測資料處理。東華大學校園面積 251 公頃，2013 年可以飛行 250 公尺高，校園拍攝 1.5 小時 552 幅影像(地面解析度 5.8 公分)、約 1 天內可以產製校園 2.5D 影像地圖。2021 年東華大學藝術學院歷時 12 年完工後需要建立新的校園航照影像地圖，但目前 90%東華大學飛行限高 60 公尺，所以同樣校園 2.5D 拍攝需要超過 1 萬張影像(重疊 80%影像)，單獨建築有超過 20 棟、8 個以上學生宿舍群與教師宿舍需要側向拍攝，通常飛行高度 60 公尺，一個 20 分鐘飛行航次有 400 張垂直影像可以建立 2.5D 影像地圖，一棟建築 20 分鐘飛行航次有 400 張垂直與傾斜影像建立 3D 影像地圖，地面解析度 1-2 公分。預估無人機飛行次數超過 50 個航次、總飛行時間超過 16 小時。

經過約 2 年 3 次課程超過 10 位同學課堂上以 DJI Mini3 Pro/DJI Mavic 3 與 DJI Phantom 4 RTK 無人機進行校園拍攝超過 20 棟建築約 8000 張垂直/傾斜影像與校園 14487 張垂直影像拍攝，每幅 2 千萬像素影像資料約 4-5Mb，所有原始影像資料約 90Gb。資料處理使用 Pix4Dmapper 與 Reality Capture 兩種軟體，前者比較適合處理 2.5D 影像地圖、後者處理3D影像地圖有比較好的成果。平均地面解析度2公分，使用軟體內建相機校正、沒有另外進行相機校正影像準確度介於 5-10 個像素，所以 3D 地圖準確度介於 10-20 公分，進行拍攝場地相機校正(Field Camera Calibration)後 3D 地圖準確度提升至 2-5 公分。學生課堂中學習無人機各種飛行技巧、資料收集方法、相機校正、地面控制點設計、RTK-GPS 測量控制點與自然色/多光譜相機影像資料處理、3D 建模與 3D 地圖建立等整合型目標導向的地球科學教育。

關鍵字: 3D 地圖、 攝影測量、即時動態全球衛星定位、場地相機校正

Integrated earth science education: creating a 3D NDHU campus map using digital photogrammetry

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Traditional methods of Earth Science education acquire earth surface information such as geomorphology, rock/structure distribution, land use types and plant distribution. Such information is very difficult to obtain since you need to apply them from different sources and even thought you have the data and you do not have the training to use those data. This have changed in the last 10 years as the unmanned aerial vehicle (UAV)emerging in the market with affordable price. It has equipped with camera, multi/hyper spectral camera, rtk-gps and lidar systems, the earth surface information is much easier to collect by fewer sources and even by yourself. It is therefore very important that you understand how to use these data through integrated earth science education.

In this study, we select the course training data from digital photogrammetry course in NDHU, this is a MSc course of 3 credits, students will learn background information including UAV, multi/hyper spectral camera, rtk-gps and 3d data processing methods, at the same time they will need to learn how to fly a drone and collect image data. NDHU's 251-hectare campus is Taiwan's largest flat land university campus were surveyed in 2013 using Sensefly eBee UAV. The flying height was 250m and it took 1.5 hours to acquire 552 images to build a 2.5D map with a ground resolution of 5.8 cm. Since the complete of the NDHU Art College building in 2021, there is a need to have a new 3D NDHU campus map. The UAV flying height limit in NDHU campus is 60 meters now, it is therefore need to collect more than 10,000 images to build a 2.5 D campus map and another 8000 image of individual building is need to create 3D NDHU building map. The flying time for the course training should be more than 50 flights and 16 hours for NDHU campus project.

More than 10 students within 2 year time, they used DJI Mini3 Pro/DJI Mavic 3 and DJI Phantom 4 RTK drones, and collected more than 8000 vertical/oblique images of NDHU campus buildings and 14,487 campus vertical images. The 20 Mpixels image is about 4-5 Mb each and the total image size is about 90 Gb. They have been trained to process 2.5 D data using Pix4D Mapper and 3D data using Reality Capture. The overall groud resolution is 2 cm. If we only use default camera calibration of Pix4D Mapper or Reality Capture, the accuracy is 5-10 pixels (10-20 cm). On the other hand, if we proceed a field camera calibration, the accuracy improves to 2-5 cm. During this integrated course training, the students are able to learn the UAV flying skills, how to collect data, camera calibration, ground control point (GCP) design, RTK-GPS and GCPs survey, drone image processing/postprocessing and creating 3D model/Map.

Keywords: 3D map、 Photogrammetry、RTK-GPS、Field Camera Calibration

知識網地質出版品網站之蛻變

The Transformation of the GSMMA Publication Website

劉明哲[1]、李怡璇[1]、劉羽珊[2]、陳政恒[2]、黃芷馨[2]、張閔翔[2]、張碩芳[2]、黃智昭[2]、郭麗秋[2]、侯進雄[2]
Ming-Che Liu[1], Yi-Hsuan Lee[1], Yu-Shan Liu[2], Gem-Heng Chen[2], Chih-Hsin Huang[2], Min-Hsiang Chang[2], Shou-Fang Chang[2], Chih-Chao Huang[2], Li-Chiou Kuo[2], Chin-Shyong Hou[2]
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(1) Hyweb technology Co. LTD.; (2) Geological Survey and Mining Management Agency, MOEA

摘　要

臺灣擁有多樣的地質景觀，各界對於其形成與演育進行調查研究，累積豐富的地質文獻；「臺灣地質知識服務網」是經濟部地質調查及礦業管理中心（地礦中心）整合地質文獻知識的平台，自建置供應至今已提供20年以上之服務。其中，「地質出版品」網站以公開地質相關出版品為主要用途，包含地質學、地質調查、地質圖、研究報告等相關領域的書籍、期刊、報告和其他出版物。地質出版品網站以Java語言，採N tiers & MVC架構為主，輔以文字探勘（Text Mining）、分類（Classification），提供不同領域的資料體驗。因應網站趨勢與載具使用的變化，為求使用者更好的使用體驗，預定於113年地質出版品網站升級為響應式（Responsive web design，RWD）平台，提供在不同行動裝置都能有更便利及友善化的操作行為。

臺灣地質知識網絡推動與發展計畫為滿足使用者更多地質知識、資料查詢等需求，將地礦中心調查地質成果、研究報告、地質環境、地質災害、研究論文、地質圖、工程地質與環境資源等相關報告，予以分類呈現重要出版品，例如1.年報：這是經濟部中央地質調查所（地礦中心前身）每年出版的報告，記錄了該年度的地質調查成果、研究報告和相關資訊；2.特刊：涵蓋特定主題或特定地區的地質研究，例如礦產資源、地質災害、地質環境等；3.彙刊：定期出版的地質學期刊，包含了各種地質學研究論文、報告和新知；4.地質季刊：以促進地質科學之學術交流及推廣地質教育為使命。

新版網站將透過活潑、簡潔的畫面，輔以RWD設計，提供民眾閱覽時，隨時可透過行動載具閱覽出版品記載之地質資訊，以提升知識網站供應地質知識之效益。

關鍵字：地質出版品、地質知識、響應式網頁設計、資料庫
Keyword：GSMMA Publication, Geological knowledge, Responsive web design, Database

創意地質旅遊成果與應用

Achievement and Application of Geotourism

莊勝傑[1]、古佳慧[1]、林建緯[1]、廖偉勝[1]、劉羽珊[2]、郭麗秋[2]、張閔翔[2]、董英宏[2]、
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摘要

臺灣擁有多樣的地質景觀，具有科學、生態、遊憩、防災、經濟與社會等多元價值。其中，為地質景觀提供解說和服務設施，使遊客獲得美學上之賞析外，還包含了地質知識之獲得，這種旅遊型態是為地質旅遊。地質旅遊不只是具有地質知識的旅遊方式，亦可發展出精緻化觀光行程，進而成為在地社群經濟活動，帶入環境保育及地質教育之議題，提升環境意識，實踐永續目標。

《地質》期刊自101年9月開始推出「創意地質旅遊」專題，加上原有「知性旅遊」、「大地寫真」、「地質教室」等專欄、部分地質專題等與地質旅遊直接相關文章累積將近200篇，地質景點涵蓋臺灣本島、離島與外島，並依區域與主題規劃出近百條地質旅遊路線。創意地質旅遊成果除了刊載於紙本期刊，並將電子檔案公開上網於臺灣地質知識服務網提供瀏覽、下載，也綜整地質主題、區域地質景點再加上周遭人文、產業特色資訊，以旅遊手冊形式發行各區域「地質賞析之旅手冊」，應用於地質賞析活動，或於當地行動博物館展示、官方、民間旅遊資訊站進行推廣。線上運用部分，另結合行動定位服務(LBS)功能，於臺灣地質知識遊APP進行地質景點推播；現今則配合智慧型手機與線上地圖使用習慣，

將賞析手冊點位、主題內容建置於Google Maps，透過臺灣地質知識服務網、臉書粉絲專頁等媒介推播，無論是教學上地質考察路線，還是深度、知性的地質旅遊，皆能輕鬆可及地質景點與賞析路線的資訊與知識。

關鍵字：創意地質旅遊、地質賞析之旅手冊、地質季刊、百大地質路線
Key words: Geotourism, Geology Outdoor Appreciation Manuals, Ti-Chih, Top 100 geological appreciation routes

工程地質探勘資料庫於資源探勘及土地開發上之應用

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摘　要

隨著能源需求的增加以及土地利用需求的變化，地質空間資訊的應用也日益重要。地質空間資訊包括了地質構造、岩層分布、地下水位及斷層等等，這些資訊對於資源探勘、土地開發與管理上具有相當大的參考價值。工程地質探勘資料庫系統是經濟部地質調查及礦業管理中心所開發建置之空間資料庫系統，主要用於蒐集、儲存與管理全國地質鑽探、取樣及試驗等地質探勘資料。透過此系統可以獲取地下空間資訊，進而應用於資源探勘及土地開發管理等領域。

近年由於全球對清潔能源的需求不斷增加，地熱能做為一種清潔能源得到了越來越廣泛的關注。地熱能利用地下深處的高溫岩石來發電或供暖，是一種非常有效的能源利用方式。然而，要想進行地熱能的探勘，必須先取得地質探勘資料。利用工程地質探勘資料庫系統所蒐集及公開的資訊，可以更好地取得、分析和加值應用這些資料，進而實現更好的地熱能探勘。通過分析地下岩石的熱傳導性、熱容量、地溫分布等特性，可以協助確定地熱能的潛在資源，從而發展更好的地熱能開發計畫。

在土地開發與管理方面，都市計畫的區域地質特性是一個最前端也最重要的考量因素。如果開發區域存在活動斷層或破碎岩盤等地質條件，將可能對建築物的安全造成威脅。透過工程地質探勘資料庫系統，可以獲取開發區域的基本地質資訊，進而建立三維地質模型。這些資訊可以用於建築物的結構設計以及地質災害風險評估；此外，在土地開發前，需要對該土地進行詳細的地質調查和評估，以確保該土地的使用是安全和可行的，而這些調查和研究皆需要足夠的鑽探資料和地質資訊，運用工程地質探勘資料庫系統，可以迅速將這些資料整合起來，提供更好的空間決策。

工程地質探勘資料庫系統經過加值應用，能夠更準確地評估地下地質環境，避免發生地質災害，而隨著國家淨零政策的推動發展，工程地質探勘資料庫系統的應用也將越來越廣泛，成為未來國土永續發展的重要工具。

關鍵字：工程地質探勘資料、淨零、永續發展

都會區建物地震風險分析系統之建置

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摘　要

近年來台灣經濟、城市快速發展，都會區人口、大樓密度也不斷成長，地震災害威脅對居民的生命財產也不斷增加。從以往災害地震事件記錄得知，房屋毀損不僅導致人員傷亡，倒塌廢棄物也可能造成道路中斷，間接影響人員搶救、傷患運輸等。如果能夠精確的分析都會區建物可能面臨的地震風險，篩選出都會區建物的弱點，推動適當的防治計畫，將可以有效降低災害性地震帶來的威脅。因此如何提升都會區建物地震風險分析的精確度，對都會區而言是一件非常重要的防治工作。本研究採用簡化的建物模式(Xiong,2017)配合時間歷時分析方法，使用MATLAB程式語言建立都會區建物地震風險分析系統，系統只需要用到建物基本GIS資料(例如樓房高度、樓地板面積、構造類別、建造年代等)即可完成分析。系統本身採用模組化設計，模組間是互相獨立，各模組透過資料交換界面進行資料轉移，減少系統記憶體的使用量和改進計算效率。本研究以示範區為例，採用地震情境模擬方式，整合強地動模擬反應、建物時間歷時分析與動態展示技術，說明系統應用於都會區地震風險分析的可行性。最後，系統的分析成果透過三維的視覺化展示平台展示，顯示地震風險分析系統能夠有效應用於都會區防災、減災規畫工作。

關鍵字：地震風險分析、地震情境模擬、視覺化展示平台

臺灣西部海域離岸風場海域洋流及地質環境分析-海纜共同上岸廊道盤點與地質敏感區分析

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摘　要

臺灣能源政策規劃再生能源配比預計在2025年達到百分之20，其中離岸風電的裝置容量規劃需要 5.7GW，現階段離岸風電開發主要以固定式離岸風機為主，風場主要分布在台中至雲林一帶外海及新竹至苗栗近岸，已設置完成的裝置容量達到 1.7GW，為達到政策規畫目標未來將有更多風場於臺灣海峽設置；離岸風電所產生電力均需透過輸出海纜，經由臺灣電力公司所公告的 9 處「海纜共同上岸廊道」將離岸風場併入電網，然而臺灣位處活動板塊邊緣使地質活動頻繁，在西部產生許多活動斷層，因此共同廊道周圍是否存在地質災害風險有其重要性，且未來隨著離岸風場的增設已規劃的上岸廊道也會逐漸飽和，本研究將蒐集現有地質敏感區資料對 9 處共同廊道進行地質敏感區分析，並依循臺灣電力公司共同廊道選址相關準則，提出在臺灣西部沿岸未來可以增設共同廊道的位置。初步地質敏感區分析顯示，竹南、通霄、安風及中清廊道區域附近有活動斷層通過，後龍廊道附近的斧頭坑斷層目前雖未有證據顯示其為活動斷層，但斷層有切過頭嵙山層，顯示斧頭山斷層至少為更新世斷層，多數廊道皆位於沖積層所覆蓋區域，沿岸沖積層普遍具有程度不一的土壤液化潛勢，其中安風、中清、港風、彰化北側及彰化南側廊道均有中、高程度的土壤液化潛勢。

關鍵字：離岸風電、共同廊道、地質敏感區分析

土壤液化潛勢調查與公開計畫
Investigation and disclosure of soil liquefaction susceptibility

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摘要

105年0206地震後，經濟部地質調查及礦業管理中心為土壤液化潛勢圖公開之中央主管機關，負責土壤液化潛勢調查及公開作業，自107年執行「土壤液化調查與公開」計畫，目的為加強土壤液化災害潛勢評估，精進液化調查分析方法，以及完善防災地質資訊。

本計畫共分為3個部分：(1)調查精進與資訊網包含微振動測量及查詢網站更新與維護，其中微振動測量採用非破壞性之地表微振動量測，進行地盤特性調查，以彰化縣崙雅里5處調查點結果顯示其地盤卓越週期介於2之間，本量測對於地盤週期與環境自然頻率可快速取得調查區域之地盤特性。土壤液化查詢系統提供圖資成果查詢，並介接內政部防災避難地點位置，可查詢鄰近避難處資訊，顯示門牌所在位置之3D地質資訊、3D尺標顯示地下深度資訊與工程地質分區圖，提供民眾更多元豐富之資訊。(2)地盤改良工法透過降低地下水位及格子狀地中壁等方式進行案例分析，評估改良前後二維靜態殘餘變形分析之垂直沉陷分布，成果顯示降低地下水位可有效抑制土壤液化對地表既有建物之危害，而地中壁改良後建築物產生液化差異沉陷，因此仍須謹慎檢討受震液化引致差異沉陷對上部結構物的可能危害。(3)地下水文統計與分層架構建置則利用基隆市248處、新竹縣(市) 1,563處、苗栗縣724處、南投縣907處、花蓮縣1,167處及臺東縣511處地質鑽探資料，建置其三維地下水文分層架構，藉以改善土壤液化潛勢評估時，設定地下水文參數之合理性與代表性不足之問題。

經濟部地質調查及礦業管理中心致力於土壤液化潛勢調查，107年啟動「土壤液化調查與公開」計畫，提供更全面的防災地質資訊，積極面對都會區地質災害防治。

中文關鍵字：土壤液化、微振動量測、地下水、地盤改良
Keywords: soil liquefactionr, micro-vibration measurement, groundwate, ground improvement

土壤液化圖資創新與防治技術發展計畫
Innovation of susceptibility maps and development of prevention technology for soil liquefication

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摘要

地質調查及礦業管理中心為延續原安家固園計畫未完成之工作，並達到地質資料整合、智慧防災科技應用、災害觀測物聯網建置、本土化抗液化地質改善技術與應用圖資建置等目的，故提出本計畫，提供未來防災規劃參考。

本計畫共分4個部分進行：1.風險地圖產製與監測場址建置的部分，為建構三維地質模型資料庫，針對研究範圍之鑽孔資料予以整合，建構一套具有地質與地層空間分布意義之三維地質模型；另外，考量不同震源之發震機率與建物條件，針對台中、彰化與南投縣平原地區新產製土壤液化風險地圖3幅，更新臺北、新北、宜蘭與台南市之圖資4幅；並選定於臺中市民主議政園區與花蓮市國盛抽水站等2處建置土壤液化監測示範站。2.應用動態循環三軸試驗精進之部分，建立國內的動態循環三軸試驗數據之資料庫；將液化土壤動態資訊增列於《工程地質圖集》(臺北盆地、宜蘭平原部分)之各工程區，並配合土壤動態強度輔助土壤液化評估法進行分析。3.淺層地下水位動態模式評估方面，為建立水文地質架構與地下水位即時預測模型，利用貝氏最大熵法進行岩性推估，建構一水文地質參數場；透過時空間特徵分析法及機器學習演算法LSTM，建立臺北盆地之地下水位即時預測模式，將成果展示於網路平臺並提供下載。4.針對圓錐貫入試驗分析液化土層方面，建立海域圓錐貫入試驗之資料庫，並於陸域進行圓錐貫入試驗調查，提出圓錐貫入試驗土壤液化分析方法修正建議；另外，本年度已於大灣國小完成土壤液化超額孔隙水壓監測站示範站建置。

中文關鍵字：土壤液化、三維地質模型資料庫
Keywords: soil liquefaction, 3-D geological model database

土壤液化調查與風險評估計畫
Investigation and risk assessment of soil liquefaction

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摘要

行政院於109年核定「土壤液化調查與風險評估計畫」並交由經濟部執行，以接續內政部執行「安家固園計畫」；其計畫承繼了過去調查成果並更進一步全盤規劃調查策略。

經濟部地質調查及礦業管理中心自110年起，已陸續與18縣市政府團隊通力合作，展開全面性都會區地質調查工作，並全數完成第一階段工作，在補充鑽探部分，將分為岩心全取樣之地質井，以進行地層判視，及工程井進行標準貫入試驗與提取劈管取樣分析，目前完成鑽孔數已達3200孔，並設置自記式水位監測井約350孔及人工地下水位監測井約2850孔，並將這些豐富資料已收入於地質資料庫中；另外為了提升計畫成果，完成12處以上的老舊建築物與地下管線之風險評估，相關成果於各縣市辦理教育宣導。

未來期望透過更高品質鑽探調查及更高密度之鑽孔資料蒐集，預期將完備國土防災圖資8,000平方公里，將三維地質資料庫健全，並開放供各界使用，由此資料庫納入工程案開發，除可降低探勘所需經費與時間，更可提供政府進行重大決策之參考。

中文關鍵字：土壤液化、風險評估
Keywords: soil liquefaction, risk assessment

以岩象學及 X 光繞射分析低度變質碎屑岩雲母特徵之研究

The characteristics of mica of low-grade clastic metamorphic rock by petrography and X-ray diffraction

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摘要

一般而言，當我們探討臺灣極低度至低度變質碎屑岩區的變質程度時，常常以“伊萊石結晶度值”作為變質度高低之依據，但是，尚未考慮岩石中碎屑源白雲母、已變質的白雲母及變質作用產生的絹雲母等對於“伊萊石結晶度值”之貢獻程度。因此，本研究將以岩象學分析岩石中雲母礦物特徵及 X 光繞射分析儀分析黏土礦物種類、伊萊石多型及伊萊石結晶度值，作為不同種類雲母礦物對於伊萊石結晶度的貢獻程度之依據。

本研究分析結果顯示，粉砂質板岩的伊萊石結晶度為 0.254-0.285，劈理間距較密，夾質領域的石英顆粒因旋轉而具方向性排列，碎屑源白雲母顆粒介於 20-150 um 之間，碎屑源白雲母顆粒周圍已有絹雲母產生的白雲母顆粒介於 20-250 um 之間，伊萊石多型有 2M1+1M，其中碎屑源白雲母顆粒周圍已有絹雲母產生的白雲母顆粒越大時，伊萊石多型 1M 特徵峰越多。變質砂岩的的伊萊石結晶度為 0.22-0.291，劈理間距較疏，夾質領域的石英顆粒因旋轉而具方向性排列且顆粒間已呈現縫合線現象，碎屑源白雲母顆粒介於 60-300 um 之間，碎屑源

白雲母顆粒周圍已有絹雲母產生的白雲母顆粒介於 20-200 um 之間，伊萊石多型皆為 2M1+1M。就目前研究結果得知，白雲母種類和顆粒大小會表現於伊萊石特徵峰，但是，對於伊萊石結晶度質並沒有顯著相關性。

關鍵字：低度變質碎屑岩、伊萊石多型、雲母
Keywords: low-grade clastic metamorphic rock, illite polytype, mica

以Micro-XRF技術探討Esquel橄欖隕鐵之礦物學特徵

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摘　要

本研究以掃描微區光譜儀(Micro X-ray fluorescence spectrometry；Micro-XRF)對Esquel橄欖隕鐵切面(68x31公分)進行大區域的元素分布、礦物相及微組構分析。Esquel橄欖隕鐵元素分布圖顯示：（1）礦物組成包含橄欖石（58%）、鐵紋石（26%）、鎳紋石（10%）、隕硫鐵（1.7% ）、隕磷鐵鎳礦（1.5%）、鉻鐵礦（0.7%），以及磷酸鹽類（1.6%；隕磷鈉鎂鈣石或隕磷鎂鈣石）；（2）橄欖石明顯含有錳、鋅及砷等微量元素。Esquel橄欖隕鐵中之橄欖石形態可大致區分出兩類，均勻分散的角狀橄欖石及於局部集中的橄欖石聚集體。不同類之橄欖石在錳、鋅及砷等微量元素的含量及分布變化亦有明顯差異。這些結果顯示Esquel橄欖隕鐵具有多階段的形成歷程，且過程中亦包含撞擊事件。

Magma replenishment, metasomatism and hydrothermal fluid infiltration paths of Talun grainite batholith: regional structures and crystal defects

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Abstract

Regional geologic reconnaissance coupled with petrographic observations showed the hierarchical metallogenesis paths for the granitic batholith exposed at Talun creek, East Taiwan. The granitic magma replenishment and Al-Si-K-Fe-S-O-C-H enriched hydrothermal fluid infiltration occurred accordantly or in an entangled manner in the Wulu schist including areas around Hsinwu bridge in the E and Wulu/Liukou areas NW to leave flame-like ore deposits. Such ore veins, mainly with metal sulphides, REE minerals (monazite, allanite, and minor oxides/carbonates) and occasional noble metals (Au,Ag,Pt), tended to distribute along the NS-strike faults and tension cracks not only in the Talun creek and Wulu creek in the North, but also in the pillow lava associated with mica-rich green schist in the East of Hsinwu bridge. The magma-replenished felsic veins/domains at the proximity of black schist with occasional carbonate at the interface were frequently decorated with pyrrhotite. This is accountable by the Fe-S-bearing fluid being introduced via the Al-Si-K veinlets from almost isochemical schists for pyrrhotite formation upon contact metasomatism. Microscopically, the ore deposits were found to prevail along grain boundaries, sub-grain boundaries and cleavages of the quartz-feldspathic crystals and free surface of the rocks/pebbles, indicating a metallogenic process via the short-circuit diffusion paths. The tenor of native gold or REE ore is either rich or poor with respect to the ferrimagnetic pyrrhotite, depending on the extent of liquid-phase separation and crystal fractionation of the replenished magma and hydrothermal solutions in the T-P-C-t and space paths of the region.

Solidification, metamorphism/metasomatism and metallogenesis of Talun granite

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Abstract

Talun granite pebbles recovered near the outcrop at Talun creek, East Taiwan were characterized by polarized optical microscopy and electron microscopy as the type-I alkali feldspar granite with hyper- and sub-solvus Or-Ab solidification textures more or less obliterated by metamorphism/metasomatism and metallogenesis upon crustal emplacement at orogenic wedge of the subduction zone. The metamorphism involved Kfs reacting with pelitic metasediments to form Ms and myrmekite Qtz as inclusions in Ab coupled with the formation of high temperature-stabilized Rt. Meanwile dynamic deformation was manifested by the creep polygonization/fragmentation and vitrification/sintering reassembly of Qtz+Fsp for reorientation within the pristine Kfs toward the optimum crystallographic orientation relationship. There are also refractory Ti-Y-Nb-O phases which are accountable by mantle signature upon an intermediate episode of pluton subduction and then entrapped within Grt/All and Ilm for Fe-Mn partitioning upon exhumation. The subsequent metasomatism resulted in Al-Si-K rich veinlets to introduce Fe-S fluid for the occurrence of Rt+Zrn+Py+Pyh. The ferrimagnetic Pyh is monoclinic Fe7S8 with characteristic magnetic hysteresis and low-T transition behavior to act as an indicator of metallogenesis for granite-related ore deposits, in particular the occasionally observed microparticles of native gold and LREE,Y,Tl-Mnz. (Note minerals abbreviation follows the IMA scheme)

Study on the flux-grown lanarkites and their luminescence properties

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Two kinds of lanarkites (Pb_2SO_5) of various crystal qualities were formed simultaneously as accessories in a flux-grown anglesite ($PbSO_4$) experiments. Both synthetic lanarkites crystallize into a monoclinic symmetry with a space group of C2/m. Identical to the natural specimens, the cell parameters are a=13.746 Å , b=5.710 Å , c=7.065 Å , and =β115.75° for the poor-quality lanarkite and a=13.749 Å , b=5.702 Å , c=7.069 Å , and =β115.72° for the good-quality crystal. The structure refinements give the final R factors of 5.4% and 2.1% for the poor-quality and good-quality lanarkites, respectively. The WDS chemical analysis suggests an oxygen-deficient lanarkite for the poor-quality crystals. The XRD examination indicates that the poor-quality lanarkites have decomposed into anglesite and cerrusite ($PbCO_3$) after being ground into powder and then stored for 5 years. When exposed to UV light, the powder emits a strong orange fluorescence. After being heated to 600°C, the two crystalline phases reacted with each other and reversibly changed back to lanarkite, but the orange fluorescence disappeared. For comparison purposes, lanarkite powder has also been synthesized through the solid state reaction at 700°C. Its band-gap is 3.0 eV from both the UV/Vis diffuse reflectance data and first-principles calculation. The synthesized powder does not fluoresce when illuminated with 325 nm light. However, the bright yellow fluorescence can be observed in the good-quality lanarkites. Their fluorescence intensity weakens as the temperature increases, and even disappears above 300°C, but the fluorescence reappears after being cooled to RT. Further, the blue-shift of PL spectra was observed with the temperature rising. As a result, this study proposes possible mechanisms by which these two different lanarkites can exhibit fluorescence.

The provenance and geochemical characteristic of heavy minerals offshore northern Taiwan

臺灣北部海域重礦物物源與地球化學特徵

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Abstract

The offshore northern Taiwan are adjacent to the areas of the Tatun Volcanic Group and the Keelung Volcanic Group, with outcrops of Tertiary sedimentary rocks along the coast. The region is also known for the famous Jinguashi gold-copper deposit. Offshore islands such as Pengjia Islet, Huaping Islet, and Mianhua Islet are composed of volcanic rocks. Due to the different heavy minerals compose of igneous rocks, sedimentary rocks, and ore veins, the provenance of sediments in this marine area can be traced back based on these geological features. This study focuses on the mineral composition and geochemical analysis of surface sediments and rock core sediments in the northern waters of Taiwan, as well as surface sediments on beaches.

The main components of heavy minerals include magnetite, pyroxene, and amphibole, with additional minerals such as ilmenite, limonite, zircon, garnet, apatite, biotite, pyrite, marcasite, and monazite. The results indicate that heavy minerals primarily originate from nearby andesite, supplemented by a small amount of Tertiary sedimentary rocks. There is no significant variation in the individual proportions of heavy minerals in a single core sediment, except occasional enrichment of marcasite. Sediments near the mouth of the Jiufen River show an enrichment of pyrite, and the proportion of pyrite increases towards the shore, suggesting a relation with the output of the Jinguashi deposit.

Nearshore sediments exhibit a trend of enrichment in rare earth elements (REEs) towards the northeast, transitioning from heavy REE enrichment to light REE enrichment and showing a scarcity of heavy REEs. This trend may be related to the increase in apatite or monazite towards the northeast.

Key words: offshore northern Taiwan, heavy minerals, rare earth elements, provenance of sediments

台灣西南部古冷泉碳酸鹽成岩過程中穩定同位素組成之意義

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摘　要

冷泉碳酸鹽岩是甲烷滲漏系統的重要產物，海床上碳酸鹽膠結的成因是深處儲集層中的油氣沿著斷層裂隙向上滲漏，進入淺部的孔隙率較高的砂岩層，被厭氧性古菌氧化而造成碳酸鹽膠結。因此，這種由甲烷引發的碳酸鹽膠結可以作為探勘區域內是否有油源的指標且記錄了油氣滲漏活動和流體組成隨時間的變化過程。

台灣西南部地區具油氣蘊藏潛能且研究區域存在許多泥貫入體，在地表造成多處泥火山地形。而泥火山在噴發時伴隨天然氣逸出，其穩定同位素組成顯示其形成來源之差異。這些不同類型的油氣來源，均有可能透過裂隙在微生物的作用下形成碳酸鹽岩。本研究採集大崗山、甲仙及那瑪夏地區所之不同產狀之碳酸鹽岩。其中塊狀之碳酸鹽岩選取未經風化部分進行研磨；管狀之碳酸鹽岩則沿其橫切面細部取樣後進行研磨進行穩定同位素分析，追蹤其可能來源。

本研究依其產狀及分析結果進行討論如下:(1)大型角礫狀團塊，其碳同位素顯現一致的特徵，其與現今古亭坑背斜區的天然氣苗同位素組成極為近似；(2)巨型煙囪狀之中心與基質部分明顯為兩種不同期次岩性所組成。中心部分為灰白色顯晶方解石脈所充填，並由中心向外分布。其碳同位素組成自最外緣往內部趨向高值。外圍基質部分所記錄的碳同位素組成，與現今甲仙地區的天然氣苗同位素組成相似，中心灰白色顯晶方解石脈部分，則與地下水之無機碳酸鹽之碳同位素組成較為接近，顯見中心流體通道部分在後期抬升至地表後，被地下水的同位素置換；(3) 細管狀網絡。外型似同心圓柱，由內緣(圓柱中心)至外層取樣。其碳同位素值組成一致且被地下水的碳同位素所置換。顯見不同產狀所顯示之碳同位素組成則有所差異，並間接證明冷泉碳酸鹽岩的產狀與其碳源有極大的關聯。最後參照地層中與其共生的二枚貝類等生物化石群落，其地層年代的控制，將本區氣苗活動的時間往前跨至距今約一千萬年前源自深層熱成熟天然氣的活動證據，說明本區石油系統已有效運作，其油氣產物已向上移棲至海床表層逸出。

關鍵字: 冷泉碳酸鹽、穩定同位素、台灣西南部

印尼 Seram 島地質構造剖面建置

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摘　要

Seram 島位於印尼東側的馬魯古省(Maluku province)，屬班達島弧(Banda Arc)的北部區域，因班達海板塊(Banda Sea Plate)與澳洲板塊(Australian Plate)的碰撞形成褶皺逆衝帶的構造形貌。Seram 島的陸上油氣探勘仍處於初期階段，探勘資料缺乏，目前的發現包含 Bula 油田、Oseil 油田、Lofin 氣田，三者皆位於 Seram 島的中至東部，其中 Lofin 油田為印尼近年的重要發現之一，顯示 Seram 島東部陸上區域確實具有探勘潛力。本研究利用前人的野外地質調查資料與 Shuttle Radar Topography Mission(SRTM)地形資料，建立數值地質圖，並在 Seram 島東部與中部參考地質圖與鄰近井資料，以急折法各建置一條地質構造剖面，以增進對該區域地質的認知，並可作為後續探勘與研究工作的基礎，如重力模擬等等。東部剖面結果顯示從西南至東北存在逆衝斷塊、背斜褶皺與向斜褶皺，其造成的地層褶曲逐漸減緩；中部剖面結果顯示存在一雙坪(Duplex)構造，使中生代地層 Kanikeh Formation 重複出露地表，底部滑脫面存在一斷坡，使滑脫面東北側深度較西南側淺，並在 Lofin 氣田附近存在一構造三角帶。

關鍵字：地質圖、構造剖面。

微區螢光光譜分析儀協助標註岩石薄片礦物分割之方法

A method of Labeling Mineral Segmentation Assisted by Micro X-ray Fluorescence

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岩石薄片岩象分析是計算儲集岩礦物組成的方法，其中石英、長石、岩屑和基質是沉積岩分類中常使用的端成分。在偏光顯微鏡下分辨該礦物為長石，往往得透過旋轉載物台，觀察礦物是否有一條條黑白並列雙晶的光性特徵，石英、岩屑和基質則無此特徵。然而長石的光學礦物特性與石英相似，許多長石顆粒因已破碎而無顯示雙晶特徵，常常無法與石英顆粒分別。故本研究透過微區螢光光譜分析儀(以下簡稱 μ-XRF)，利用其化學元素組成得到礦物分割，來協助標註岩石薄片之光學影像。

研究方法分為五個步驟：(1)岩石薄片光學影像拍攝及處理；(2)岩石薄片 μ-XRF 掃描；(3)利用 Matlab Registration Estimator App 將光學影像及 μ-XRF 掃描結果比對註冊，並轉換為標籤；(4)利用孔隙比例影像特徵替換孔隙標籤；(5)人工標註岩屑標籤及修飾其他標籤細節。

本研究將 A 井上福基砂岩層之岩石薄片使用 Olympus 光學顯微鏡進行光學影像拍攝並使用 PTGui 軟體拼接，另使用本單位之 Bruker M4 tornado 進行 μ-XRF 掃描，並將兩結果進行比對並註冊，更新許多先前人工辨識所未能辨識之長石樣本，增加長石標籤。後續將利用此更新過之礦物分割標籤進行人工智慧訓練。

關鍵字：微區螢光光譜分析儀、光性礦物、影像處理、儲集岩

Micro X-ray fluorescence、Optical Mineralogy、Image Processing、Reservoirs

增積岩體下部斜坡內逆斷層形貌初探－以國內外案例討論台灣西南海域是否可能存在向東逆斷層?

Preliminary study on the morphology of thrust faults in the lower slope of the accretionary prism - Combining domestic and foreign cases to discuss whether there is a possible eastward thrust fault in offshore southwestern Taiwan?

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摘要

台灣西南海域海床形貌受到斷層與水道切蝕作用相互影響，於變形前緣以東形成深度變化劇烈的一系列海脊與峽谷，水深變化介於 200 公尺至深於 3400 公尺間。此區域自上世紀 90 年代陸續有與地體構造相關之研究發表，更在經濟部中央地質調查所（現地礦中心）2004 年至 2015 年共三期的天然氣水合物探勘計畫與 2009 年至 2018 的兩期能源國家型科技計畫等調查內，蒐集並發表了許多構造、沉積環境、地熱與天然氣水合物之研究報告。就構造形貌而言，前人對於西南海域增積岩體區域研究多架構於薄皮逆衝理論之上，以一系列西向逆斷層形式解析增積岩體內上部與下部斜坡所見各背斜構造。然台灣西南海域除增體岩體構造外，更涵蓋了被動大陸邊緣之大陸棚與大陸斜坡，其中大陸斜坡區域傳統上稱為台南斜坡，其概略可以澎湖水道為界線，與東側位處於增積岩體之高屏斜坡相分隔。此兩不同構造形式對於構造形貌的影響，過往之研究較未著墨。

根據國外發表文獻，可知被動大陸邊緣構造形貌除正斷層系統外，在遠離被動大陸邊緣之深海盆地方向，仍有逆斷層構造之形成；另部分於不同區域的增積岩體研究亦指出，可能發育與增積岩體推擠方向相反的逆斷層。故本研究以蒐集並彙整歷史文獻方式，討論台灣西南海域增積岩體下部斜坡範圍內，除前人所認為之西向逆斷層外，是否具東向逆斷層之存在。藉由彙整國外增積岩體與台灣陸域麓山帶相關研究，本研究認為台灣西南海域應於兩構造區域可能出現東向逆斷層，分別為:1.被動大陸邊緣鏟型正斷層往東側延伸至與增積岩體相互重疊區域；2.增積岩體基底滑脫面具斷坡處。

中文關鍵字：台灣西南海域、增積岩體、台南盆地

Keywords: offshore southwestern Taiwan, accretionary prism, Tainan basin

台灣西南海域構造恢復研究

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摘要

台灣西南部海域的台南盆地在傳統或非傳統油氣資源上都被認為是前景可期的區域，也是近年台灣周邊地區深水油氣探勘的主要目標。此區域跨越主動式與被動式邊緣，有著複雜的地形轉折與大地構造地質背景。在前人研究中，已經完成台南盆地淺水區（陸棚區）到深水區（陸坡至盆底區）之古沉積環境重建及斷層之走向與傾角方向之描繪。本研究結合淺水區與深水區之震測資料進行構造恢復研究，以釐清各時期的盆地形貌、地質架構，進而對台灣西南部陸海域的油氣探勘有所啟發。

本研究使用台南盆地內震測資料，結合井下層序劃分結果進行震測層面與構造解釋，從中挑選兩條具代表性之剖面進行構造恢復與反剝分析，剖面 A 位於北部凹陷內，剖面 B 橫跨北部凹陷、中央隆起帶與南部凹陷，兩條剖面皆完成漸新世早期、漸新世晚期、中新世早期、中新世晚期與上新世晚期五個時期的構造恢復。剖面恢復結果顯示北部凹陷發育於漸新世晚期至中新世早期，並在中新世晚期最為活躍；中央隆起帶於中新世形成構造高區；南部凹陷於中新世晚期受到台灣造山運動影響，形成一系列逆衝斷層，南部凹陷與中央隆起帶交界區域於上新世因重力滑坡形成鏟形斷層，並影響逆衝斷層帶前緣的形貌。

關鍵字：台南盆地、構造恢復、油氣探勘

印尼 E 礦區井測資料分析

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摘要

印尼 E 礦區為本公司海外重要油氣探勘標的之一，透過地球物理分析，礦區內已發現多個好景區及遠景區，為進一步確認礦區開發之潛力，本研究將藉由鄰近礦區之鑽井資料及鑽探試驗成果釐清礦區之地質情形。

本研究的探勘標的為中生代的 M 層，在取得之資料中，共有 5 口井到達此地層，分別為 L-1 井、L-2 井、O-1 井、O-2 井及 O-4 井。本研究針對電測資料、岩屑資料及井壁岩心等資料進行分析，利用這些臨近礦區之井資料，推測出野貓井之各地層深度，降低鑽探風險。

關鍵詞：井測分析、印尼 E 礦區

印尼海域E礦區震測解釋

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摘要

E 礦區位於印尼東部馬魯古省，鄰近巴布亞省西南方外海之 Seram 島上。本礦區位於 Seram 盆地，屬於低度探勘區域，其油氣主要儲集於中生代侏羅系之碳酸鹽岩中，亦可儲集於新生代淺層之上新統砂岩中，根據前人研究指出其複雜構造區具有一定的油氣潛力。本研究利用礦區之 F 層與 M 層等二儲集層進行海域震測資料解釋，透過海域架構建置及被動大陸邊緣之震測相解釋。陸棚沉積環境其震測相呈平行狀和低起伏之丘狀之反射形貌，陸棚邊緣和往外退覆的斜坡系統則涵蓋較厚之海相沉積物，並發展成 S 狀型態和偏斜外伸之往外退覆之反射形貌，進入盆地底部則以深水扇體為主。研究結果顯示濁流砂體可和反轉背斜構兩種探勘標的可做為未來持續探勘之參考。

關鍵詞: 印尼海域、F 層、M 層
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印尼 Seram 島石油系統研究

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摘要

本研究根據印尼 Seram 島現有油氣田/發現，分析其中生代石油系統各項要素，以瞭解各要素之特點及增進對中生代石油系統之認識。分析結果指出中生代石油系統之儲集層為 Manusela 地層，生油岩可能包括 Kanikeh 地層及 Saman-Saman 地層的頁岩，主要蓋岩為 Kola Shale 地層。

Kanikeh 地層年代為中至晚三疊紀，其盆地相為廣泛堆積之頁岩，總有機碳含量(TOC)為 0.69–3.73%，生油潛能普通至優良。Saman-Saman 地層年代為晚三疊紀至早侏羅紀，由代表深水相之頁岩，泥質石灰岩及泥灰岩構成，生油潛能在普通等級(TOC=0.92%)。Manusela 地層即 Saman-Saman 地層之等效淺水相地層，以碳酸鹽岩為主。由於 Manusela 地層較緻密，故孔隙率通常為可忽略至貧乏等級。然此儲層具廣泛裂隙系統，能顯著提升儲集能力及滲透率。Kola Shale 地層年代為晚侏羅紀，為海進時期所形成之廣泛頁岩。

此石油系統之關鍵時刻為上新世早期，亦為 Banda Arc 與澳洲大陸碰撞之時(5-3Ma)。此碰撞擠壓作用不僅讓生油岩得以深埋而成熟，亦於儲集層中產生裂隙網絡，進而提升儲集品質。此外，擠壓也形成各種構造封閉及逆斷層通道，使油氣可沿逆斷層運移並積聚於新生代構造中。然擠壓也可能破壞蓋岩完整性，使原本蘊藏在中生代儲層中的油氣滲漏，增加探勘風險。

關鍵字：Banda Arc、澳洲大陸、石油系統

苗栗至澎湖外海離岸風場高解析地層及海床地貌調查

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摘要

為達到政府2025年非核家園目標，離岸風電為其中重要綠能政策之一，而海域地質條件又關係到風機基礎穩定及維運安全。地調所本於「海洋地質調查」的業務職掌，規劃在離岸風電場址進行海洋地質環境調查，提供基礎地質環境資料，補足離岸風電地質環境資料缺口。因此，自111年起地調所推動此4年期「離岸風場海域地質調查及地質環境資訊服務 （1/4）」科技計畫，並規劃於離岸風電開發區域進行詳細地質調查及地質與環境感知系統建置。

本團隊參與此4年期計畫中的「高解析地層及海床地貌調查計畫」，作業重點是探測並分析風電潛能場址的海床特徵物、海床底質特性及淺部地層構造，並繳交相關探測與分析結果供海域地質資料庫建置使用。因此，本團隊規劃於112年度計畫調查區域內進行以下5項探測作業，分別使用勵進研究船LGD2311航次以及LGD2315航次，進行以下探勘作業：多音束水深探測(收集面積432 km^2)、海床影像觀測(收集數量9.12 hrs)、底拖式高解析聲納探測(收集數量404 km)、電火花震測探測(收集數量1592 km)以及表拖式磁力探測(收集數量2192 km)，探勘規劃區域內的地質安全穩定性以及地質構造，各項作業項目皆有達到合約要求的數量。

離岸風場開發進度規劃中，第三階段開發風場包含去年調查範圍D7潛能風場以及苗栗外海D5潛能風場，本年度的調查區域範圍由澎湖海域延伸至新竹苗栗外海區域，其中包含的潛能風場有鄰近澎湖海域的D9、D10和D11風場已及新竹苗栗外海的D4、D5和D6風場。其中D9、D10和D11風場主要以電火花震測資料及隨船的多音束水深、船載底質剖面資料為主，以及部分特徵地區的海床影像觀測資料；D4、D5和D6風場中，資料包含多音束水深資料、測線間距2公里的底拖聲納資料以及電火花震測資料涵蓋此調查區域。

電火花震測資料主要涵蓋的範圍橫跨由澎湖外海至新竹苗栗外海調查區域，藉以了解整個區域中層至淺層的地質架構，以電火花震測剖面展示到500公尺深

的地層資料（以速度1700 m/s換算），剖面主要觀察到末次冰盛期不整合面、最大海漫面以及沙脊基底面等3個近海床層序，以及澎湖和苗栗區域的地區型不整合面。本團隊並進一步的將近海床層序作為地質分布圖，以了解其平均深度以及分布趨勢，其中沙脊基底面的深度約為40~97 m深，最大海漫面的深度約為60~110 m深，末次冰盛期不整合面的深度約為60~140 m深。底拖聲納資料則集中在D5潛能風場區域，底質剖面中顯示淺部地層中夾帶許多聲波反白帶訊號特徵以及強反射層面，顯示此區域地層的非均質性較高，除此特徵之外，於底拖側掃聲納影像與多音束水深的影像中，皆觀察到數個海床特徵物分布，其中包含位於苗栗外海的不礙航沈船特徵物，沈船尺寸約為長120 m、寬19 m、高25 m。多音束水深資料涵蓋部分D8潛能風場區域，於D8風場中觀察到大量的海床侵蝕特徵，顯示強烈底流的作業環境。

海床影像探測完成澎湖外海之海床觀測調查，共計執行7條測線，累積之海床攝影測線長度約為6.43公里、海床攝影時間約為9.12小時。位於D9風場的T08測站觀察到貝屑、小型隆堆以及珊瑚。位於D10風場的T06測站觀察海床主要為沙質海床，並觀察到少量碎石以及底棲生物，位於D11風場的T01測站觀察有許多岩塊以及T04測站觀察到海床表面出現貝屑以及小型隆堆。

綜合各項探測結果歸納本年度調查範圍 3 種潛在的地質影響因子包括聲波反白帶、強反射面、淺層斷層。由電火花震測發現的聲波反白帶分布於澎湖水道及彰濱外海鄰近 D7 風場的區域，底拖聲納的聲波反白帶則大量集中於苗栗外海，顯示這些區域沉積物非均質性高，可能與流體有關。澎湖群島周邊及澎湖水道廣泛分布強反射面，且離澎湖群島愈遠愈深，可能與火成活動的玄武岩分布有關；苗栗外海也有許多強反射層的分布，然而層厚僅 1~2 公尺，分布範圍零散，較可能是河道沖積的礫石層，由於分布的深度較淺，對風場基礎施工存有安全影響。澎湖群島周緣和苗栗外海分布著許多淺於 120 公尺的斷層，可能在距今 1 萬多年間曾經活動，D9、D10、D11 風場有許多此類斷層分布。北部風場新竹苗栗外海 D4、D5 和 D6 風場也存在許多淺部斷層分布以及出露海床背斜構造，顯示此地區為地質相當構造活躍的區域。相較位於彰雲砂脊北側的斷層則多未切穿海面下 120 公尺深度的地層，活動性較低。

澳洲西北海域 W 礦區震測資料解釋初探

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摘　要

W 礦區位在澳洲西北海域的 Oobagooma 次盆地，此一次盆地為古生代張裂盆地-坎寧盆地(Canning Basin)位在海域的一部分。盆地構造形貌特徵延續了在其東側(陸側)，同樣也位在坎寧盆地北部的 Fitzroy 地槽，次盆地中央為東西向至西北西-東南東走向的凹陷區域，是盆地中主要的沉積物堆積區域，北側及南側則與周圍高區接壤。W 礦區所在的海域坎寧區域(包含羅巴克盆地(Roebuck Basin)與坎寧盆地的海域部分)在過去屬於相對較低密度探勘活動區域，直到近年在此區域的深部地層發現大型油氣田後，才開始有較密集的探勘活動進入。本研究利用 W 礦區內新採集與處理之 2D PSTM 多頻道反射震測資料，進行震測資料分析，尋找具有探勘潛能的區域。並且與周圍鑽探井位的資訊結合，進行合成震波比對，藉由比對出的目標面時間-深度關係，讓井下的層面資訊在能套用到震測剖面上，解釋時即能夠摘取各層面的正確位置。坎寧盆地自古生代早期張裂形成後，堆積了厚層的沉積物，估計在 W 礦區下的古生代地層最厚可達約 10 公里。由於整個區域在古生代受到多期的構造活動影響，震測剖面上的地層訊號顯示出各種程度不一的傾斜與褶皺，並有明顯的斷層發育。中生代早期則經歷了 Fitzroy 運動，造成區域內的地層抬升，導致大部分三疊紀至早侏羅紀地層被侵蝕。Fitzroy 運動結束後礦區內處在較為穩定且沒有明顯構造活動的時期，此期間中生代的地層大部分訊號連續性良好，且能夠清楚觀察到地層層序。根據震測解釋的成果，初步認為 W 礦區有數種可能儲集油氣的探勘標的類型，未來將持續對此礦區進行更深入的分析研究，以更進一步解析礦區內的油氣潛能。

中文關鍵字：澳洲西北海域、坎寧盆地、反射震測資料解釋、合成震波比對
Keywords: Offshore Northwest Australia, Canning Basin, Reflection Seismic Data interpretation, Synthetic Seismogram

利用井測與重力數據應用於印尼礦區油氣探勘

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摘要

本研究礦區位於印尼東部，屬於低度探勘區域，其油氣主要儲集於中生代侏羅系之碳酸鹽岩中，亦可儲集於新生代淺層之上新統砂岩中，根據前人研究指出其複雜構造區具有一定的油氣資源潛力。根據現有探勘資料中取得多條二維震測線，其中重力資料則包含區域大尺度重力、磁力及地形資料，並且取得 2001 年新採集的陸上布蓋重力異常數據。礦區內位於濱海淺部儲集層鑽探的井測數據有 6 口。前述井測資料目前都僅有常規井測如伽瑪、電阻率、自然電位等數據，針對現有資料進行岩石物理參數計算，如頁岩含量、孔隙率、含水飽和率與岩相分類，然而這 6 口井並非均具備完整可用之密度及聲波走時測錄數據，本研究進行一系列資料處理後再行應用。此外，後續為針對陸域深部儲集層之地層分層深度比對及震測資料解釋，分別蒐集了 5 口鄰近油氣田之數據資料，並進行詳加比對與分析。本研究以先前礦區周遭的地質地物探勘資料為基礎，使用地表地質圖進行目標礦區地下地質剖面之建構，藉由鄰近礦區之井下實際地質分層與鑽探試驗成果，搭配現有井測分析，進行兩條二維重力順推模擬，重新檢視中生代石油系統成藏分析。

Application of Drone thermal camera in Guguan geothermal exploration Area

無人機熱像儀於谷關地熱潛勢區之應用

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近年來國內產官學界積極投入無人機(UAV)發展，快速累積無人載具基礎研究之能量。UAV可承載多元儀器，如傳統相機、多光譜及空載光達等，應用於社會民生、防救災運輸以及基礎科學等。由於目前在熱像儀應用著墨甚少，然熱相儀其特點為可以在夜間進行施測，在反映地物特徵以及溫度分布上具有很大的優勢。本團隊應用多元尺度遙測技術進行地熱徵兆探測，前期使用美國陸地衛星Landsat熱紅外光空間解析度為100米，可呈現區域性裸露岩石的溫度狀況。後續規劃導入無人機搭載熱像儀沿大甲溪谷關及馬陵兩處溫泉區進行河谷拍攝工作，其影像空間解析度20公分，溫差敏感度可達正負2度間。最後配合現地野外調查的方式進行水溫量測、獲取溫泉露頭資訊，進而評估本研究區域之地熱徵兆分布。本研究使用美國陸地衛星Landsat 8 TIR資料結果顯示，在谷關地區其地表高溫呈現線狀的型態；而馬陵區域其地表高溫呈現點狀分布的型態，藉此初步成果規劃後續UAV熱相儀飛行任務區域。以谷關地區為例，本團隊於112年7月19-21日進行拍攝工作，經熱像儀熱源區域確認為谷關野溪溫泉露頭，該露頭位於虹夕諾雅溫泉會館北側之大甲溪河畔，其溫度最高溫為攝氏53.5度，pH為7.97屬弱鹼性，溫泉水無明顯沉澱物，並具有氣泡與溫泉花，且帶淡硫磺味。另於12月6-7日於台8線臨37線5.7公里處起飛，藉由熱像儀熱源區域在河床裸露地施測時熱像儀有溫度異常之反應，並沿河岸帶狀分布有地表地熱徵兆，依據熱源區域確認為鄰近馬陵野溪溫泉處，溫度高區主要集中在大甲溪北岸，其溫度最高溫為攝氏65.6度。

致謝：經濟部地質調查及礦業管理中心
計畫中文名稱：臺中市谷關地區地下三維地質模型建置
計畫英文名稱：Three-dimentional geological model construstion of the Guguan area, Taichung

關鍵字：無人載具、熱像儀、地熱徵兆、谷關溫泉區
Keywords： unmanned vehicles, thermal imaging cameras, geothermal unmanned vehicles, thermal imaging cameras, geothermal features, Guguan Hot Spring Area

高雄寶來地熱探勘：臨時密集地震網

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在近年來，用高密度地震網捕捉微小的地震訊號，並運用於地熱前期探勘已為趨勢。尤其淺層的地震斷層構造更能與地表地質觀測相互結合。因此，在此次計畫規劃佈密集的地震觀測網，以監測小型地震為主，尤其寶來地區地震發震頻繁，可以詳細的描述此區域地下的活動構造，並配合震源機制解，以探討其構造活動性。在完成微小的地震定位後，其震波走時資料也將對高解析的三維速度構造提供良好的控制。微震監測監測儀器為本團隊時常使用的三分量短週期地震儀(Smartsolo 3C)，為 5Hz 地震儀非常適合微震監測。臨時地震網佈設範圍為寶來地區，由團隊收集臨時地震網之地震資料進行微地震監測與震源機制解資料分析。設置 80 個測點，佈設 Smartsolo 三分量地震儀，監測結果顯示該區每天約有 100 多起小地震發生，震源深度在 10 公里以上，因此探測深度可達 10 公里範圍內。在臨時地震網佈設為期 1 個月，在收回資料後利用本團隊發展的 AI 地震判識系統進行地震挑選與定位，最後再進行震源機制解分析，以了解該區域裂隙與應力方向，並對照目標範圍內既有地質及地球物理探測資料綜整討論。同時在微震監測資料處理完後，所產生的地震目錄、P 波與 S 波的到時資料，本團隊進行三維震波成像逆推，以獲得 P、S 與 Vp/Vs 的震波速度構造，可以推判寶來地熱區域的活動構造與區域相對地熱高區。

以統計學分析探討宜蘭地區溫泉和地表水特徵之研究

A statistical analysis of thermal and surface waters in Ilan area

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摘要

宜蘭地區的地熱資源是臺灣地熱開發的重點區域，然而，位於低度變質碎屑岩的地熱區常常面臨一個問題-管線結垢。對於溫泉業者而言，必須經常性更換管線或是清理管線內結垢；對於地熱電廠而言，結垢使得發電量隨時間遞減，且即使清潔管線也難以恢復原本的發電量。結垢的產生是一種過飽和的現象，當原本均質的流體上升到地表的過程中，因為溫度和壓力改變使得該流體產生沉澱作用，而結垢的種類與流體的特徵有關。因此，基於上述原因，本研究首先彙整並以統計學分析宜蘭平原、清水地熱區及土場-仁澤等地區溫泉和地表水之水化學特徵；再者，分析地熱區的沉澱物，以了解沉澱物的種類；最後，整合水化學特徵、沉澱物種類，透過地球化學模擬了解不同水化學特徵可能產生沉澱物的環境。

本研究就溶液中總固體溶解度資料顯示，宜蘭平原和山麓的介於 300-1,400 mg/L 之間，溫泉區溪水以清水溪數值最低，介於 100-300 mg/L 之間，溫泉區的天狗溪山壁溫泉數值最低 800-1,200 mg/L 之間。就酸鹼值結果顯示，清水地熱區溪水及溫泉的數值最高，約為 9.5-8 之間；其他地區的酸鹼值大致相同，介於 8.3-6.5 之間。就陰離子分類結果顯示，溫泉區以碳酸氫根及碳酸根為主要組成；宜蘭平原、山麓及溫泉區河水的硫酸根含量略低於碳酸氫根及碳酸根含量。就陽離子分類結果顯示，宜蘭平原、山麓及溫泉區河水的鈣和鎂離子高於鈉和鉀離子；溫泉區除了天狗溪山壁溫泉的鈣和鎂離子高於鈉和鉀離子之外，其餘溫泉的鈉和鉀離子高於鈣和鎂離子。未來將進一步將不同區域的溫泉和地表水以統計學

分析其相關性，再分析地熱區的沉澱物，以了解沉澱物的種類；最後，整合水化學特徵、沉澱物種類，透過地球化學模擬了解不同水化學特徵可能產生沉澱物的環境。

關鍵字：統計學、溫泉、地表水、宜蘭

Keywords: statistics analysis, thermal water, surface water, Ilan

金崙地熱系統與區域水文間影響之量化評估

Quantitative assessment of the interaction between Jinlun geothermal system and regional hydrology.

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摘要

考量國內地熱潛能區多位處山區變質岩帶，其地熱流體的流動多受構造活動產生的裂隙主導，相較於國外火山型與沉積岩型地熱田，流體資源的掌握難度門檻較高。為建立適用於國內山區水文地質系統之地熱資源評估方法，本研究將調查東部金崙地熱開發區地下水補注以及水質分布狀況，為地熱開發之儲集層管理方案提供學術性證據，工作項目主要可分為兩項，分別為(1)區域地表水文循環模式建立與(2)區域水文與地熱系統間之影響量化評估。

目前已監測為期三年之水文數據，利用「區域水文循環方法」、「河川流域水文現地觀測方法」及「流域水文河川消退曲線分析方法」，計算出金崙地區自然補注量約為7,100萬噸。經由地化之元素濃度、氫氧同位素、鍶同位素與氦同位素分析結果，金崙地區的熱水入滲來源高程約1,670~2,100 m，其中溫泉水上部儲集層比例約達90~98%，地熱井之地熱水上部儲集層來源比例約76~91%，且熱源非岩漿活動形成。若計算水來源高程分布之面積(約13.51平方公里)，其佔整體金崙溪流域面積8.9%，續依此面積比例及金崙溪流域自然補注量綜合計算，得此高程範圍之自然年補注量約為630萬噸。

綜合以上成果，儘管得出金崙區域之地下水補注量，但水文調查通常需要長時間收集大量數據，以精確評估水文系統的特徵變化與趨勢。後續將持續更新地化及水文監測數據，完善金崙地熱開發區之水文循環模式。

關鍵字：地熱系統、地球化學、水文地質

Keyword：Geothermal system、Geochemistry、Hydrogeology

大屯山馬槽地區地熱儲蓋系統研究

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摘　要

依據過去地熱鑽探井資料，大屯山地熱系統在馬槽地區具有最高的地溫梯度，且曾產出弱酸性熱水，但是對於地下弱酸性熱水分布的瞭解相當侷限。為了進一步掌握弱酸性熱水之分布，本研究以儲蓋系統的地熱概念模式為基礎，透過馬槽地區新探井井下岩屑與岩心礦物相分析進行熱液換質帶分類，進而辨識儲集層及蓋層分布。

岩屑與岩心礦物相分析得到 60 至 750 公尺屬地熱系統中的蓋層(黏土化帶)，並於 760 公尺始探獲儲集層(青磐岩化帶)，其代表性黏土礦物指示溫度大於 200°C。此外 X 光粉末繞射分析發現有方解石的存在，岩心觀察亦發現裂隙存在方解石脈，指示地下流體可能為非酸性，然其化學性質仍需待產能測試流體取樣分析後方能證實。井下測溫資料顯示 450 公尺(161°C)至 750 公尺(243°C)呈溫度陡升之異常地溫梯度現象，岩心觀察亦於 760 公尺至 780 公尺間發現斷層擦痕及破碎帶，推論此異常高溫現象係深部高溫熱液透過裂隙上湧所致。

藉由馬槽新探井所獲得之地下溫度資料、裂隙(斷層)與儲集層分布及可能存在非酸性流體等資訊，可供後續建構大屯山馬槽地區完整的地熱系統。

關鍵字：地熱儲蓋系統、礦物相、熱液換質帶

東埔溫泉野外地質構造初探與地熱構造研析

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摘　要

台灣位處於歐亞板塊與菲律賓海板塊隱沒碰撞帶上，特殊的地理位置使本島擁有豐富的溫泉與地熱資源。而在地熱資源開發的議題上，如何有效評估導水裂隙與應力之間的關聯性，於先期評估的調查上甚為重要。

野外構造量測主要針對地熱徵兆區，進行野外露頭量測與觀察，目的是為了能進一步探究熱水上湧通道與地質構造的關聯探討，提供地熱概念模式的建立與運用，並可將其成果供給後續詳細調查階段與場址調階段之使用。

過去依經濟部地質調查及礦業管理中心的台灣溫泉網顯示，本調查區包含東埔溫泉與樂樂溫泉等兩個野溪溫泉範圍，在地質單元分類上屬於雪山山脈地質區。東埔溫泉出露於十八重溪層中，岩性由黑色至深灰色板岩所組成，夾薄層變質砂岩，在本層內彩虹瀑布下游，夾有火成岩體，產狀呈脈狀分布，岩性以輝綠斑岩質侵入岩，為本區最大火成岩體出露(市村毅，1936；林朝棨與周瑞燉，1974；陳勉銘，2016)，過去認為該火成岩體與東埔溫泉之熱水活動有所關聯(張寶堂，1984；李春生，2000)；而樂樂溫泉則出露於達見砂岩中，岩性由淺灰色厚層、粗粒至細礫石英質砂岩或變質砂岩組成，間夾板岩、硬頁岩以及少量石灰質變質砂岩。陳有蘭溪樂樂溫泉附近出露有綠色砂岩及岩脈(陳勉銘，2016)。

依據樂樂溫泉野外露頭量測結果推斷，水裡坑斷層可能為本區主要深切構造，而在樂樂溫泉區可以觀察到斷層錯移的結果，並形成兩種不同的露頭產

狀。部分地區以斷層泥與斷層角礫岩為主，可能形成一良好阻水封阻構造，因此地表未發現徵兆出露，而在局部地區以斷層破碎岩產狀為主，可沿著此斷層構造將深部熱水帶至淺處，並形成目前樂樂溫泉主要徵兆區。水裡坑斷層依據前人調查與古應力斷層擦痕反演結果，為一左移的斷層構造，並且大地應力由西北-東南向擠壓為本區主要特徵。該應力場環境在淺部開裂了西北-東南向的節理系統與褶皺背斜後期的斜張破裂(軸部與板劈理面)，也可能在地下深處發育了西北-東南向的破裂系統，並且在達見砂岩中，形成良好的地熱儲集層，隨著水裡坑斷層移棲至地表，伴隨本區裂隙系統與板劈理之斜張破裂，強化了熱水上湧的有效通道，形成樂樂溫泉之地表徵兆。由地熱徵兆位於河谷右岸與斷層上盤研判，樂樂溫泉的地熱儲集層與熱源，應在水裡坑斷層的北邊地下深處，在本團隊大地電磁法(MT)結果得到相似的論證，而上湧的深切構造則透過水裡坑斷層成為本區主要的路徑通道。

關鍵字：東埔溫泉，樂樂溫泉，水裡坑斷層，應力，地熱徵兆，大地電磁法。
Keywords: TungPu hot spring, Le-Le Hot Spring, Shuilikeng Fault, Stress, Geothermal Indicators, Magneto-Telluric method.

增強型地熱概論與岩石三軸試驗於EGS的應用

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摘　要

台灣期望能在2050年之前，實現「淨零碳排」目標，而「能源轉型」會是重點方向之一。繼現有的太陽能與風力發電等再生能源開展多年後，為了再加速永續能源進展，「地熱發電」會是新階段的生力軍。目前台灣對於淺層地熱的研究相對多，不過也遇到了地下熱水分布不如預期等等的挑戰。若希望台灣順利達成規劃進度，須得擴展至「深層地熱」的運用，而現今許多國家開發永續能源的主流正是「增強型地熱系統 Enhanced Geothermal System，EGS」。EGS這種地熱能源技術，是通過在一端鑿井注入冷水、吸收地底熱能，再由另一口井抽出熱水，獲得能源，是連難以直接取得地下熱水的區域也能夠運用的方式，也是相對淺層地熱，選擇地區上更為彈性的地熱能源選擇。

使用EGS方式發電時，需要注入液體到特定深度加壓，使岩石產生裂隙。然而，施加的液壓如果太大，超出岩石強度上限，可能誘發地震。其中一知名例子是2017韓國浦項市規模5.4的地震，是自1978年以來該國第二大的地震事件，便被認為與增強型地熱電廠的發電方式有一定關聯。因此，若希望找出能源擷取與災害避免的平衡點，研究岩石的相關參數就會變得至關重要。本研究預計使用中央大學的岩石力學相關設備，取得岩石的強度、滲透率等岩石物理參數，並使用2024年中央研究院將於宜蘭員山執行一口4.5公里的學術井樣品。日後搭配未來鑽掘獲得之破裂面方向和現地應力等重要資訊，我們期望能將相關參數與研究成果能實際應用於台灣的EGS發電。

谷關溫泉區地質資料與地熱潛能初勘

Geological data and preliminary exploration of geothermal potential in the Guguan Area

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摘要

由於極端氣候對於人類生存環境的威脅日趨嚴峻，全球已有超過 130 國家提出「2050 淨零排放」的宣示與行動。為了朝向多元化再生能源發展，政府於 2022 年正式將地熱能列為前瞻能源發展重點之一。然而根據經濟部能源署資料顯示，截至 2024 年初地熱開發量僅月約 7.29MW，遠遠低於深層地熱能評估可開發量 40GW。除了地熱開發前期投入成本甚巨、風險高以外，多數地熱潛勢區位於偏遠地區，一旦進入開發階段時，輸電電網相關配套建設工程，亦讓投資方望之卻步。谷關溫泉自日治時代開發至今，位於大甲溪多處溫泉露頭地表溫度可達 60 餘度；另上游地區多處水力發電廠，具有先天上電網完整性的優勢，自 2023 年成為經濟部地質調查及礦業發展中心西部五處地熱潛勢調查區之一。

本計畫彙整前人相關地質調查成果，將多張不同比例之地質圖進行系統性數值化工作，其中將岩層位態、岩性分層、區域構造以及地表地熱特徵等套疊於高精度光達數值地質模型資料。由於本區位於雪山山脈地質區其地質岩性差異大、構造延續性佳，因此透過地表地質調查成果，能進一步確認地表露頭有助於進行區域性影像判釋成果。此外，為了深入評估本區地熱潛能，本團隊在谷關與馬陵兩溫泉露頭間布設 30 處大地電磁觀測點，同時在谷關地區輔以地電阻法以利於釐清近地表熱液裂隙分佈。另本研究區在谷關溫泉區現存有高達 23 口溫泉井，以及數處位於大甲溪之野溪溫泉露頭，透過不同季節溫泉水質採樣分析，亦能建構本區地表逕流與地下熱液通道之水文地質模式。

透過上述綜合資料分析，谷關溫泉區位於谷關與谷關東斷層為深部熱液上湧的重要通道，其中白冷層東卯段為變質砂岩及板砂互層應為谷關地區主要的地下熱液儲集層。透過岩芯鑽探成果顯示本區受因斷層作用普遍存在破碎帶與熱液交換的現象，為谷關地區主要的地熱潛能分布區域。另大地電磁初步成果顯示低電阻反應深部的熱水儲集層，由大甲溪北側馬陵溫泉附近區域之高程約地下 4 公里處，沿著東北-西南向破碎帶往西南向上移棲至谷關一帶。透過地球化學分析成果顯示谷關地區各溫泉井之間，其泉質化學成分(pH 值、陰陽離子等)不盡相同，應該受到不同比例的天水混合。本團隊後續擬建置三維地下構造模式，將各項成

果導入現有調查資料，以期利用經驗公式逆推地熱儲集層之溫度，以期完善谷關溫泉區之地熱潛能評估工作。

誌謝：本研究計畫承蒙 經濟部地質調查與礦業管理中心「臺中市谷關地區地下三維模型建置」計畫案提供研究經費 謹致謝忱。

關鍵字：地熱探勘、大地電磁、地球化學、谷關

keyword: Geothermal Exploration, Magnetotelluric method, Geochemistry, Guguan

台灣大屯火山群（TVG）紗帽山地熱潛能區地熱概念模型與地熱資源量評估

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再生能源是永續的潔淨能源。利用再生能源進行發電可有效降低二氧化碳的排放。再生能源中的地熱能是從地球的儲能地層中進行取熱發電，所以不會受天氣影響而可以做為基載再生能源。台灣在 2050 年要達到零碳電力，所以台灣急需要地熱這一種基載型的再生能源來供應電力。

台灣位於環太平洋火環帶而擁有相當豐富的地熱能源。台灣的傳統地熱潛能估計約 989MW，其中，臺灣北部的大屯火山群地熱區的發電潛能即超過 500 MW。若要加速台灣的地熱能源建置，大屯火山群的地熱能源開發相當重要。

本研究的主要目的是針對大屯火山群的紗帽山地區進行地熱資源探查。作為未來鑽井探勘前的準備，本研究主要進行地熱地質研究以建立研究區域的地下三維地熱概念模型，並依此評估研究區域的地熱資源量。

本研究主要是啟動野外地質調查以探明地熱儲集層的岩性以及紗帽山地區鄰近之可能構造與裂隙。依據野外地質調查所記錄的岩性和井下地質解釋，建立本區域地熱概念模型並建立三維地熱地質模式以進行熱儲量評估。

本研究利用地質剖面、井下資料、該地區之 DEM 資料、對構造的判斷、野外補充調查之成果來建立一紗帽山地區之地質模型，根據模型可以更直觀得到紗帽山地區有約 750 公尺厚之安山岩、2300 公尺厚之地熱儲集層，其中，根據鄰近鑽井資料，安山岩最高溫達 174^{0}C 、儲集層之最高溫達 240^{0}C。此外，該地區存在許多高角度斷層，這些斷層具有成為良好地熱通道之條件，因此，在模型建立時，也加入了本地區之5 條斷層，以期模型能更加完善。

透過完善的地質模型建立後，匯入數值模擬軟體，進行紗帽山地熱潛勢區的熱儲量評估，研究範圍為紗帽山的周圍 12 平方公里，透過井資料與補充調查之成果設定溫度、孔隙率、滲透率、相對滲透率、完井設計等模型參數，本研究將生產開發年限假設為 20 年，根據體積法發電潛能估算結果約為 241.36 MWe，換算為能量結果約為 152.23 Pje。

高雄寶來地區地熱地質探勘

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摘　要

寶來地熱區位於臺灣南部地溫梯度較高的區域，具有地熱開發潛能，其鄰近地區的地下水（熱）循環與淺層地熱能萃取，受控於斷層及大型破裂帶的分佈，其中潮州斷層為東北—西南走向的左移兼具逆衝特性的斷層，分隔西部麓山帶與輕度變質岩區域的脊樑山脈；另一可能的破裂帶或變形帶:美瓏山斷層，大約平行潮州斷層，位於荖濃溪東側，然尚未被明確報導過，僅少數前人研究推論美瓏山斷層的可能分佈位置與錯動方向。本團隊針對寶來地區主要地熱徵兆區以及鄰近區域進行地質調查，初步顯示寶來市區東側有複雜的斷層破裂系統。藉由河床與林道上斷層兩側出露岩性明顯的不同，以及斷層兩側在岩層傾向與劈理位態上有明顯急劇地改變，研判美瓏山斷層確實存在。根據寶來舊溫泉頭、石洞溫泉、五坑溫泉與七坑溫泉等溫泉的分布主要沿著美瓏山斷層上盤，且僅在美瓏山斷層上盤部分裂隙或斷層觀察到熱液換質帶出露，推斷美瓏山斷層應為寶來地熱區良好的阻水構造。

根據空載光達資料影像判釋與野外裂隙調查成果，斷層及裂隙構造在美瓏山斷層兩側有明顯不同，在美瓏山斷層下盤，主要為東北—西南走向，傾向向東南，少數為西北—東南走向，傾向向東北；在美瓏山斷層上盤，主要有 5 組裂隙及斷層: A.東北西南向，傾向向東南；B.西北東南向，傾向向東北的裂隙；C.近南北向，傾向向西的左移斷層；D.東北西南向，傾向向西北的逆斷層；E.西北東南向，傾向向東北的正斷層，傾角較 B 陡。藉由不同露頭野外所觀察到的不同組之截切關係，研判五組構造由老到新分別為 A、D、B、E、C。 根據五坑溫泉出水裂隙皆為 C 組斷層研判其可能為美瓏山斷層上盤重要的流體通道。

關鍵字: 寶來、地熱、裂隙

非彈性應變回復法現地應力評估的統計分析與精進

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隨著科技文明的進步、經濟發展的提升，及為追求更高的生活品質，人們對於天然資源與能源開採、工程開發和廢棄物處置等各項需求也日與俱增。在這些發展的促使與推動下，地下開挖工程逐步普遍，也因此現地應力的量測及資訊趨於重要。現地應力的量測有諸多方法，如套鑽法、水力破裂和非彈性應變回復法等。其中以非彈性應變回復法(Anelastic Strain Recovery，ASR)為目前成本耗費較低與效率較高的現地應力測量方法(孫東生等人，2014)。ASR 法是以鑽井獲取地下深處岩心，藉由量測應力解壓後所產生的應變回復資料進以推算三維現地應力方向和規模的方法。

前人以非彈性應變回復法來進行應力場的規模回推，其解析方式是使用 18 個黏貼於岩芯的應變計測量 9 個方向的回復正應變規模，以最小平方法重建三維應變張量，進行三維主應變場的演算，轉換成主應力方向與規模。但得到的結果只有一組平均數值，且並未分析各主應變方向與規模的偏差量，以致無法說明數據的可信度，提供工程單位參考使用。本研究進行應變計配置與分析程式的改進，將原本 9 個方向應變數據改以 6 個獨立方向為一組單位，並於每個獨立方向使用 4 個應變計進行量測，再利用最小平方法與奇異值分解法重建應變張量，之後以共變異數進行機率與統計的計算，以數值的變數變化程度和期望值進行分析比較。

實驗樣本取於臺東南橫大崙溪，深度 140 米之片岩樣本。ASR 實驗黏貼 24 隻應變計，數據初步分析結果顯示為非典型安德森斷層應力場形式。最大、次大和最小主應變之位態分別為 141.14°/45.79°E、36.22°/14.05°E 和 293.74°/40.81°W，水平最大應力的擠壓方向為西北-東南向，主應力由大到小分別為 3.66、2.22 和 2.06 MPa。葉理傾向和傾角分別為 296.18°和 65.31°，葉理面的法向量與三軸主應變相距較遠，推測本樣本可能沒受到葉理面力學異相性的影響。

後續將得到的數據結果進行統計與總結，使 ASR 實驗應力精度的可信度增加。

關鍵字:非彈性應變回復法、現地應力
英文關鍵字: Anelastic Strain Recovery, in situ stress

宜蘭地熱區裂隙活化趨勢分析

以芃芃溫泉、排谷溪、土場仁澤為例

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摘要

臺灣因應第 26 屆聯合國氣候峰會（COP26）所提出的全球溫室氣體排放量在 2050 年達到淨零排放之目標，正積極推動地熱發電以實現能源轉型。目前臺灣已有 24 處運轉或開發中的地熱案場，總裝置容量約為 61.75MW，如何達到 2050 年 6GW 的目標，則更需要仰賴大規模的前期探勘工作。前人研究資料指出宜蘭地區地表有多處溫泉與噴氣孔等地熱徵兆，配合鑽探資料推算的高地溫梯度顯示宜蘭地區可能為良好的地熱潛能場址。

本研究以蘭陽溪北岸與南岸的芃芃溫泉與排骨溪以及土場與仁澤為例，研究裂隙成為地熱流體通道的潛能，以數值高程模型判釋出地表線型構造，經球型變異分析及投影角篩選後取得可信度較高之地表線型，再整合大地應力場及野外地質調查的成果，評估裂隙與應力場及地質構造的關係，進而分析每條裂隙活化程度及分布密度，推測地熱可能之富集區域。運用 Play Fairway Analysis 方法，綜整對於地熱的活化趨勢因子，進行統計運算其潛能的分布區域，再將各數據因子以距離反比加權法予以不同權重疊加，進而獲得地熱區裂隙活化潛勢圖。

研究顯示芃芃溫泉與排谷溪以及土場與仁澤地區的大地應力以正斷層應力場為主，走滑斷層應力場為輔，其最大主應力方向為北北西—南南東方向擠壓。本研究所判釋地線型結合震源機制解應力反演結果顯示，芃芃溫泉與排谷

溪以南北走向高傾角裂隙的活化趨勢較高，與現地調查近南北走向的節理位態相符合；土場與仁澤地區以西北—東南走向高傾角裂隙的活化趨勢較高，與現地調查的西北至東南走向的節理位態相符合，推斷蘭陽溪南北岸之節理皆可能成為熱液的上湧通道，透過計算的破裂分布密度可找出疑是地熱的熱點區域，加上裂隙活化潛勢圖可以減少地熱探勘的風險及不確定性，促進台灣地熱探勘與開發。

關鍵字：地熱潛勢圖、地熱、宜蘭

南投縣廬山地熱區構造分析

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摘 要

因應氣候變遷與全球能源轉型，國內各產業對於再生能源皆有著迫切之需求。於眾多的再生能源中，地熱能具有穩定、佔地面積小等優勢，且我國蘊含著相當豐沛的地熱潛能，亟待後續積極開發。南投縣廬山地區蘊藏著豐富的地熱徵兆，如溫泉、高溫岩體等，然而目前對於廬山地熱區之熱液通道與其形成機制尚無瞭解，因此本研究將針對廬山地熱區構造位態與熱液礦脈之野外產狀進行細部調查，期望針對廬山地區之熱液路徑建立理論模型，並為後續相關工作奠定基礎。

本研究之研究區域集中於大魯灣溪、馬海濮溪與塔羅灣溪(廬山溫泉頭)等地區，並在野外針對地層之劈理、節理、斷層、裂隙、熱液礦脈之位態與產狀進行細部測量與觀察，並佐以玫瑰圖和等值線等投影方式分析資料，了解此區域構造裂隙發展和可能的地熱通道。

野外調查結果顯示，廬山地熱區之地層劈理走向相當一致，約為北15-35°東，傾角約介於45-70°，向東南方傾斜。節理可分為三組，第一組節理走向為北55-70°西，向西南方傾斜，傾角介於70-90°之間。第二組節理走向為北15-35°東，向西北方傾斜，傾角多介於10-30°之間。第三組節理走向為北50-60°西，向東北方傾斜，傾角多介於65-85°之間。

根據前人與本團隊研究，指出廬山地區存在著西北-東南走向、中尺度之左移斷層，此外於溫泉露頭周遭經常可觀察到一系列走向北10-50°東，向東南方傾斜的的小尺度斷層，同時也觀察到熱液礦脈如石英脈、方解石脈與水破角礫岩沿第三組節理方向填充、侵入。

綜合野外調查資料和台灣地質，廬山地熱區之構造演化與熱液通道的形成模式如下：造山運動初期，來自東南方之擠壓應力形成了廬山地區主要之褶皺與逆衝、左移斷層，並形成劈理與垂直主要構造線之橫節理。隨著造山作用持續，受抬升的地層因重力形成第二、三組兩組一系之減壓節理。部分節理隨中尺度之左移斷層剪應力影響發育為小規模之斷層，並與左移斷層相交形成破碎帶，而地表深處之熱液則隨此破裂帶擴散，並以第三組節理作為垂直方向之熱液通道。

Geothermal Potential Evaluation of Guguang, Taichung with Surface Lineaments and Fracture Reactivation Analysis

以地表構造線型與裂隙活化趨勢探討臺中谷關地熱潛能

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摘要

為了解決迫切的能源轉型議題，近年來政府評估能源多樣化的可能性。臺灣位於環太平洋火環帶上歐亞板塊與菲律賓海板塊的交界處，擁有豐富的地熱資源，且複雜的構造活動可以提供深處熱源上升之通道，因此地熱資源成為臺灣能源多元化的選項之一。為評估臺灣地熱潛能，我國加強投入發展地熱資源，探勘範圍有逐漸往臺灣西部拓展之趨勢，如谷關、廬山、東埔、關子嶺及寶來等地。本研究以谷關地區作為研究地點，將評估潛在導水裂隙位態與空間分布做為重點，以裂隙活化潛勢之觀點來探究谷關地區擁有地熱發展潛能之可能場址。

本研究大致分為線型判釋、應力反演及野外查核三部分。線型判釋將利用數值高程模型及衍生圖資以肉眼進行地表構造線型判釋，並使用三角網格法計算裂隙位態，此外為評估於探勘至開發不同階段對裂隙精確性之需求度，本研究將比對不同解析度數值地形圖之判釋結果以檢測其差異性並評估業界發展地熱資源使用圖資之最小解析度需求。應力反演部分則使用震源機制應力反演結果，進行裂隙不安定性、擴張趨勢與滑動趨勢分析，以推測較有機會成為導水通道之裂隙面位態，進一步聯合應力分析結果與各判勢線型位態解算各裂隙之活化趨勢，並以野外查核檢視活化趨勢閥值之設定，以閥值做為活化潛勢之得分基準繪製區域活化潛勢圖，以裂隙活化分析之角度標定最具地熱發展潛能之好景區分布。

初步 20 公尺解析度 DEM 線型判釋結果顯示線型的主要走向呈現東北-西南向，套疊較高解析度之數值地形圖將擁有較多的線型數量。震源機制分布顯示研

究區域中多以走向滑移斷層及逆斷層為主，應力反演結果指出谷關區域以走向滑移斷層應力場為主，最大主應力軸方位為西北傾向的近水平方向。裂隙活化分析結果顯示在西北-東南向之高傾角裂隙面將擁有較高的活化趨勢。本研究成果除了有助於谷關地區之地熱探勘外，其發展之研究方法亦可應用至其它地區，提供地熱開發及地質研究使用，增進我國地熱地質領域之發展。

關鍵字：地熱、谷關溫泉、地表線型判釋、裂隙活化分析、地熱潛勢圖

裂隙地質調查應用於花蓮地區地熱探勘

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摘　要

台灣構造運動活躍，普遍存在於地層之裂隙若形成密集連通網路，可改善地層的孔隙率與滲透率，進而在緻密岩體中形成油氣或地熱流體之裂隙儲集層(Fractured reservoir)。本公司近年之地熱探勘井，於井況許可之前提下皆施作FMI井測(Formation Micro-Imager)以取得環繞井孔之地層電阻影像，並由資料解釋獲得裂隙密度、位態、大地應力方向等。但井孔能代表之範圍有限，須配合其它調查方式方可獲得裂隙連通性或裂隙總長等空間數據，再者，諸多探勘區域尚未進入規劃鑽井階段，故野外露頭之實地測量調查仍有其必要性。

台灣東部地熱潛能區多位於低孔隙率的變質岩層，已有諸多報告指出地熱流體之儲集與流通受構造及岩體裂隙控制，並將相關參數應用於地熱資源蘊藏之評估與計算。本公司延續先前花蓮地區地熱探勘工作成果進行裂隙地質調查，應用測線法(Liner scanline sampling)、區域取樣(Areal sampling)如視窗法(Rectangular window sampling)等工作方法測量地層破裂程度，調查結果經初步分析，所見如下：

1. 調查區域整體裂隙密度與裂隙強度分布趨勢一致，裂隙數量與長度略成正相關；分析所得最大主應力方向以西北-東南向為主，最小主應力方向則以北北東-南南西向或東北-西南向為主，且有平行於區域性斷層之情形。
2. 區域性斷層兩側變質度不同的地層單位中，可分別呈現不同的裂隙位態及型態，例如高度變質岩中以叢集為主，較低度變質岩則呈叢集至帶狀分布，推測此與地層特性相關。
3. 本區之線形分析結果顯示線形主要控制因素與地表裂隙一致，區域性構造之影響較不明顯。故進行裂隙統計時加入線形資料綜合分析，可補強露頭資料提高統計效果，尤其露頭較少的區域。
4. 前次調查區域緊鄰本區北側，但本次調查所見裂隙特性似與岩性較為相關，構造之影響不甚明顯，與先前成果略有不同。此種南北十餘公里短距離內即出現變化是否為常態，空間上的界線為何，以及其與地熱徵兆分布之關聯性等問題，仍待累積更多調查與分析結果以嘗試釐清。

岩石地球化學對地熱潛勢區域開發之研究

Research on Lithogeochemistry to Geothermal Potential Area Development

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摘要

地熱探勘及開發的過程，須結合多種科學及工程方法，其中之一便是地球化學方法。地熱探勘所使用的地球化學研究，目前學界仍是以水和氣體化學為主，主要是判斷水質狀況、地熱潛在溫度、結垢-腐蝕條件、潛在熱焓量，甚至能用於地熱區開發與地下水文循環之研究。然而，地熱區的水和氣體化學特徵，卻會受制於當地地質狀況；因此，地熱區的岩石化學研究也是相當重要，除了能提供地熱水來源的判釋依據，也能得知熱水層分布、高溫水岩反應溫度，甚至利用水岩比判斷潛在熱水總量。本研究將對於地熱潛勢區的地下岩芯和地表岩石進行化學分析，並討論該潛勢區的地下環境是否含有熱水，以及水岩反應溫度。

本研究位於台東縣延平鄉紅葉村，該區域地層主要為紅葉層與馬里層。本次採集之露頭和岩芯樣本，皆為紅葉層的黑色板岩。經由微量元素和鍶同位素分析，得知岩芯樣本的不易受流體移動(如稀土和易受流體移動元素(如鋰、硼，相較露頭岩石的濃度有上升特徵；對於鍶同位素，岩芯樣本的 $^{87}Sr/^{86}Sr$ 則比露頭樣本的比值更低。為驗證岩芯樣本是否經歷熱事件，分析岩石之微量元素濃度特徵，包含加權殘餘元素總數(weighted residual element sum，簡稱 wRE和質量交換(mass change方法便能得知。其結果表示，岩芯樣本中易移動元素在 wRE 的分布有增加和減少特徵，並透過質量交換的分析，得出岩芯樣本質量有損失(約22~39%；因此，以上結果均證實岩芯有經歷過熱事件。從 $^{87}Sr/^{86}Sr$ 的變化，計算岩芯之水岩比達 10.42，進而得知區域的潛在熱水含量。另一方面，結合微量元素和水岩比之數據，可推測水岩反應之溫度；結果表示水岩反應溫度介在172~337℃之間。

透過岩石地球化學的分析，除了能得知岩石和熱水事件的關聯性，亦能協助水化學判斷地熱潛勢區的高溫水岩反應程度和溫度。未來期望進一步分析岩石中礦物分布，進一步釐清岩石和水交互作用下，礦物相變化對於地熱水元素特徵變化，以建全地熱區岩石和水的反應趨勢。

關鍵字: 地熱、水岩反應、微量元素、鍶同位素
Keyword: geothermal, water-rock interaction, trace element, Sr isotope

比較單一裂隙熱能開採循環系統及數值模擬應用於乾熱岩開發產能評估研究

Comparison of single fracture thermal energy recovery cycle system and numerical simulation applied to research on productivity estimation of hot dry rock

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摘要

依據 2024 年台灣國際地熱論壇經濟部宣示，台灣目標在 2030 年開發 200 MWe 之地熱電廠，並規劃於 2040 年增長至 2 GWe，其中有相當大的發電潛能是開發深層地熱。本研究針對深層地熱中的增強型地熱(EGS生產評估進行研究，意即針對具有高溫但滲透性低且初始狀況缺少足夠的地層流體之乾熱岩利用工程方法增加滲透率及灌入取熱流體(Dipippo,2016之地熱生產方法。

本研究之模擬情境如下所述(中油公司，2023，採用單一裂隙熱能開採循環系統計算建置一 5MWe 之地熱電廠，並以一注兩產設計進行 EGS 生產循環設計，該系統是將複雜的乾熱岩開採系統簡化成單一橢圓形鉛質方向的裂隙，並且將注入井、裂隙、生產井三者訂為熱能開採循環迴路(heat extraction loop(Tester and Smith,1977。該研究熱儲層之岩性為板岩，在熱儲層間的生產井與回注井垂直距離是 200 公尺，裂隙為圓型，熱儲層之溫度為 250℃，電廠營運 20 年後之溫度為 200℃，該文獻計算出熱波穿透深度為 48.81 公尺，總面積為 3,660,000 平方公尺。(朱正文等，2023。

接續本研究利用石油公司常使用的數值模擬軟體 Petrel，並利用其 Eclipse 模擬器建置並模擬上述單一裂隙熱能開採循環系統，並比較其結果。模擬結果發現只要流量固定，不同的裂隙滲透率數值所造成的最終溫度是相似的。根據模擬結果，該模型需要每小時 100 噸的水參與換熱，而滲透率僅要大於一個最低數值(大約是 100mD)即可達到 20 年降至 200℃之結果，與文獻設定一致。另外，由於單一裂隙法僅根據熱擴散原理計算，不考慮滲透率及水的影響，意即該方法假設為有足夠的滲透率和水量進行熱交換，所以無法得到流量數據，而僅計算所需之熱儲層體積和所需熱交換之面積，而數值模擬結果顯示，模擬條件與單一裂係法一致時，僅以控制流速可以達到指定終端溫度為目標，結果與滲透率無關，故本研究認為兩方法所得結論類似。

建議未來若有深層地熱區評估，可先用單一裂隙法做前期估算，待取得更多參數後依據單一裂隙法之結果與現場岩石性質試驗結果進行數值模擬法評估。

關鍵詞：深層地熱、地熱發電評估、乾熱岩
Deep Geothermal、Geothermal Power Potential、Hot Dry Rock

嘉義中崙地區及台南關子嶺地區之地熱含水層特性初探

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嘉義中崙地區與台南關子嶺地區地下多由沉積岩組成，岩性以泥質砂岩及泥岩為主，為地溫梯度達 45℃/km 之沉積岩型地熱。雖然淺層地層之地溫梯度普遍較台灣火成岩及變質岩區低，但是沉積岩型地熱具高孔隙率及滲透率，且發育豐富的裂隙，使含水層擁有極佳的側向連續性與儲水空間的優勢，而具有較高的熱水蘊藏量。若欲將該區開發為地熱發電廠址，需深究熱、水以及得以儲水之裂隙等三大要素的特性。對於沉積岩地區，地下水可以儲存於裂隙中，亦可儲集於孔隙中。本次研究欲針對地層孔隙及構造裂隙，初探關子嶺及中崙區域之熱水含水層特性。

本次研究主要透過彙整前人文獻並再分析，並與國外同為沉積岩型地熱的案例進行比較。首先，藉由蒐集澳洲的 Otway Basin 與德國的 Molasse Basin 之地層孔隙率、滲透率及溫度的參數，與關子嶺中崙地區之既有井下資料之孔隙率、滲透率及其他相關參數對比，試圖比較調查區域孔隙儲水之特性。並標記井下鑽遇斷層之深度，以了解裂隙較高儲水能力之區域。最後，將大地電磁測量之低電阻率和岩芯中觀察到水岩反應之深度對比。

Otway Basin 之目標層為砂岩組成之白堊紀地層—Pretty Formation，深度約 2700-3500 公尺，平均孔隙率約為 20%，滲透率達 1000mD，但熱液儲集仍以斷層為主。Molasse Basin 之鑽井目標則由碳酸鹽類組成之侏儸紀地層—Malm Formation，深度約 3400-3600 公尺，其孔隙率介於 1-17%間不等，且平均值為 5%，滲透率小於 1mD。關子嶺及中崙地區之井下資料中，關子嶺三號井越深部的地層孔隙率愈小，在南莊層及北寮層之孔隙率相對較高，兩地層之平均孔隙率約為 25-35%，位於井下 1000-1500 公尺處。另外，井下約 3000 公尺處之岩芯發現沿擦痕生長之方解石。透過與大地電磁電阻率分布與井位結合後，小於 3 歐姆米之電阻率多分佈於井下斷層附近。然而，兩個因子分別貢獻多少占比，還有待後進一步評估。

深層增強地熱系統生產概念分析

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摘要

國家再生能源政策中 2025 年地熱發電裝置容量目標為 20MW；至 2030 年擴展目標為 200MW；加入深層地熱開發至 2040 年容量目標為 2GW，依據經濟部地質調查及礦業管理中心(原經濟部中央地質調查所) 2023 年 TIGP 報告 3~6 公里深層地熱潛能為 40GW，而深層地熱發電潛能估計為 3~6.2GW。然而台灣未有深層地熱開發前例，故台灣中油公司以宜蘭平原為標的區域進行深層增強型地熱系統(EGS)生產概念分析。

本研究以地質資料及初步工程規劃 2 個面向進行，藉由地質資料盤點顯示主要具有 3 項不確定性，分別為溫度、岩性及構造不確定性，亦代表現有資料尚不足以直接進行 EGS 開發。初步工程規劃則包含：注入井與生產井井身結構設計、液裂激勵生產(Stimulation)方案規劃、注產流量保障泵浦規劃、地表和地下監測規劃及 EGS 開發整體工作流程規劃。

由於缺乏深部地質資料，故建議鑽鑿井深 4000 公尺以上深層地熱探勘井，藉由隨鑽岩屑與岩心分析，以及鑽後井測與測溫等分析，取得深部地層溫度、岩性及地下構造資料，依實際數據反饋前述 EGS 專案執行所需各項評估。

關鍵字：深層地熱、增強型地熱系統(EGS)、液裂激勵生產(Stimulation)

探討地電阻影像探測法與熱液分布之關係：以花蓮-瑞林地區為例

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摘　要

地熱潛能區之基礎探勘方法，大多利用現地地質調查、既有鑽井資料、岩心/岩屑分析、地表線型判釋、應力分析、大地電磁探測（MT）及地球化學分析等方式，以掌握研究場域內潛在的地熱儲集量能。

本研究欲在花蓮縣瑞林地區採用地電阻影像剖面探測法（Resistivity Image Profile, RIP）以詳細了解淺層地下構造及可能裂隙分布範圍。本次調查採用雙極排列法（Pole-pole array）進行施測，共計完成2條地電阻影像剖面，總長度為2610 公尺，測點間距10 公尺。

瑞林地區地質背景主要為石英雲母片岩，其變質岩之電阻率取決於破碎程度，岩體越完整電阻率越高，岩體越破碎則電阻率越低，根據其地層電阻率不同之現象，並結合井下岩心記錄，了解地下岩層性質、破碎程度及地下水分布範圍，進一步推測可能的地下構造及熱液分布範圍。

關鍵字：瑞林地區、地電阻影像剖面探測法、地下構造、熱液分布

綠島西部地表地熱地質調查研究

Surface Geothermal Geological Survey and Research in the Western Part of Green Island

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臺東縣綠島鄉的發電長期以來以柴油做為燃料，發電成本較高，同時在發電過程中也產生溫室氣體和碳排放，因此近年來在綠島已有利用地熱資源作為自主電力來源相關研究與計劃。綠島近年來之地熱探勘井，皆在東南部鄰近於地表具有地熱徵兆之朝日溫泉，且已經有對應的開發生產計劃，然而綠島主要的人口、商業及觀光活動則是位在西部，因此本研究目的為透過綠島西部的地表調查，評估此區塊使用地熱能源之可行性。

研究方法分別為透過 LiDAR 空載光達資料和野外地表裂隙核查資料，進行地下構造建模；野外岩樣採集及岩象分析和礦物組成分析，評估岩石特性；地表水樣採集進行氫氧同位素分析，評估是否有地下熱液補注至地表。

綠島區域構造位態依據地表裂隙調查結合主要斷層構造可分為兩組，分別為北偏西約 50 度傾角向西傾 55 度，以及北偏東約 53 度傾角向西傾 80 度。岩象分析結果多為安山岩質之火成岩，礦物組成以輝石或角閃石、斜長石和石基為主，孔隙率為 3.66-27.05%，平均高於 20%。氫氧同位素分析結果則指示綠島西部地表水樣皆為天水來源，並非混有與朝日溫泉同個地熱系統之地下熱液補注。由分析結果初步推論綠島西部之地熱資源，雖然具有地下構造和具高孔隙之火成岩體足夠成為地下流體之通道，但可能未有地下高溫流體，需在綠島西部鑽探勘井若要更進一步了解此區域之地熱系統。

關鍵字：綠島、火山型地熱系統、地熱地質調查

Green Island、Volcanic Geothermal System、Geothermal Geological Survey

大屯山地熱系統井下岩性與礦物相研究

Downhole Lithology and Mineralogy Study in Tatun Volcano Group Geothermal System

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大屯山地熱系統依據過去地熱鑽探井資料，在馬槽地區具有最高的地溫梯度且井下也曾產出弱酸性流體。本研究藉由馬槽地區新鑽井所取得之岩屑及岩心樣本，進行岩石薄片之岩象分析、X 光粉末繞射分析(XRD、微區螢光光譜分析(μ-XRF)和孔隙率與滲透率岩心試驗分析，得到井下岩性、礦物相和孔隙率與滲透率之結果，進而探討火山型地熱系統中蓋層、儲層、岩性和礦物相之關聯性。

研究結果指示井下深度區間於 0-1060 公尺為安山岩質火成岩，1060-1100 公尺則是沉積地層與火成岩交替出現，其中 0-60 公尺受到輕微的熱液換質作用，深度 60 公尺以下出現蒙脫石，為黏土蓋層之指示礦物，深度 150 公尺以下出現石英，透過岩石薄片之岩象確認後為多晶質石英，推斷可能在火山作用噴發過程中，夾帶原先覆蓋於地表之沉積地層之礦物，而非熱液換質作用所形成，深度 350 公尺開始出現硬石膏，深度 760 公尺蒙脫石完全消失取而代之的黏土礦物為綠泥石，因此判定深度 760 公尺為地熱系統之儲蓋邊界。

岩心試驗分析於深度區間 760-805m，由岩性產狀可以區分為火山熔岩流和火山角礫岩相互交替出現，火山角礫岩孔隙率約為 3-7%，而火山熔岩流孔隙率則為 0.5-3%，從礦物相分析結果同樣指示火山角礫岩受熱液換質程度較高，可能為除了裂隙以外之地下高溫流體流通區間。

關鍵字：大屯山、火山型地熱系統、岩性、井下換質礦物相
Tatun Volcano Group、Volcanic Geothermal System、Lithology、Downhole Alteration Mineralogy

臺灣臺東霧鹿地區野外地質及區域應力分析初探

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摘　要

地熱能作為綠色能源的重要基載能源，具有強烈的地域特點。在探勘和開發階段需要整合區域地質、地球物理和地球化學等多元資料，進行多尺度分析，以達到更高的探勘效益和降低開發風險。野外地質調查和區域應力分析在地熱能探勘和開發過程中扮演著極其重要的角色。這些工作將提供大地構造的基礎數據，有助於確定潛在的地熱資源位置和特徵，提高探勘成效，降低開發風險，同時確保地熱能的可持續利用和環境保護。

根據野外考察結果顯示，本地區的葉理構造以高角度向西傾為主要特性，橫跨不同地層單位，葉理位態皆以北東走向為主。由野外露頭量測觀察顯示，露頭尺度上可觀察到近乎平行於葉理面之次生剪切帶構造的發育，本地區剪切帶與斷層構造發育於葉理後期弱面破裂，並平行葉理構造發育剪切帶。節理構造可概分為兩種類型，其一為後期沿葉理破裂的結果，另一種類型則是西北-東南走向之節理系統。從裂隙延伸性觀察顯示，沿著葉理面後期破裂之裂隙延伸性比西北-東南向之節理發育佳。此外，平行葉理之破裂面上可觀察到斷層擦痕等滑移之跡證，這可能是構成本區主要的熱水上湧通道。

在霧鹿地區，透過震源機制解算結果顯示，區域應力的平均斷層面位態為西北－東南向。縱谷斷層地震帶應力狀態介於走滑斷層和逆斷層應力場之間，中央山脈斷層地震帶應力狀態則是介於走滑斷層和正斷層應力場之間。依據斷層擦痕應力反演結果顯示，霞末溫泉地區應力機制為走滑斷層，受到東南-西北向擠壓應力場影響；而在彩霞溫泉地區反演結果顯示，受到一東北-西南向擠壓應力場影響。

綜上研究結果，本區可觀察到疑似熱流遺跡的跡證。葉理構造後期產生的脆性破裂裂隙被填充水合礦物，應為過飽和降溫降壓所導致的沉澱現象。平行葉理後期發育的剪切帶可能構成本區的深切構造，使熱水沿著淺部西北-東南向的節理系統流竄。依據露頭觀察及前人文獻，後期所發育的脆韌性剪帶和斷層系統可能提供了熱水上湧的通道。

花蓮瑞林地區地熱潛能評估初探

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本文主要探討花蓮縣瑞穗地區地熱潛能狀況，透過前人文獻之調查井、GSMMA-RS-1 及 GSMMA-RS-2 溫度量測資料建置溫度場模型，並結合地球物理調查資料推測地下地熱儲集層分布範圍，進而進行地熱好景區範圍圈繪及地熱潛能評估。

臺灣西部海岸鹽沼與紅樹林區域沉積有機碳含量比較初探

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摘　要

臺灣沿海沉積環境充滿多樣性，沉積物中所含的有機碳儲存量能可能受到當地植披、距河口遠近、季節性降雨、人類活動等因素影響。紅樹林及鹽沼為重要的藍碳棲地，本研究分別於挖仔尾自然保留區以及高美野生動物保護區進行岩芯採樣。透過岩芯描述、總有機碳、總氮分析，可對沉積環境有初步的認識。

本研究針對挖仔尾紅樹林棲地與高美濕地兩沉積環境進行評估，進行總有機碳(total organic carbon, TOC)、總氮(total nitrogen, TN)、易變有機碳(labile organic carbon, LOC)、難分解有機碳(refractory organic carbon, ROC)等比較，分析挖仔尾一 30 m 長岩芯以及高美兩根約 1 m 岩芯。挖子尾自然保留區為水筆仔紅樹林環境，其根部結構能阻擋波浪侵蝕、將枯落物有效攔截至林內。挖子尾地區呈現多次砂泥互層的變化，並且在表層 0-25 cm 處有大量植物碎屑。本研究數據顯示，上部 40 cm 的 TOC 高達 1.5%，以 LOC 為主，其餘大多數深度的 TOC 約落在 0.2-0.4%左右，LOC 與 ROC 的比例則較為接近，10-15 m、20-25 m 碳酸鈣相對較多的區域，LOC 的比例下降。TN 則呈現與 TOC 類似的趨勢，在上部 40 cm 後自 0.08%下降至 0.03%。高美野生動物保護區為潮汐鹽沼環境，植被較為稀少。在岩芯上部 70 cm 多為泥質沉積物夾植物根莖，底部為礫石層。根據元素分析的結果，TOC 最高達到 1.8%，隨著深度增加逐漸下降，LOC/ TOC 也隨著深度從約 60%下降到約 40%，TN 從約 0.05%下降到 0.02%。

本研究亦透過岩芯分析中 TOC、LOC 與 ROC 的相關比率，初步判斷挖仔尾紅樹林地區為同時受到陸地以及海洋不同有機碳來源影響的沉積環境，高美濕地位於礫石層之上，推測此區應在特定大型事件後形成暫時穩定的沉積環境。沉積物中有機碳的組成受植物分布、淡水注入等情形所影響，多變的沿海沉積環境值得繼續探究，以期建立完整的碳儲存量能評估，提供學界、公私部門在永續發展規劃下的參考依據。

關鍵字:總有機碳、紅樹林、藍碳、碳匯

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鐵砧山碳封存示範計畫之前期場址評估及基線調查

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摘　要

配合政府2050淨零排放目標以及因應未來大量減碳需求，台灣中油公司積極推動碳捕捉及封存計畫，目前選定苗栗通霄鐵砧山地區執行碳封存之示範計畫，以驗證碳封存技術在我國陸域地層實行之可行性及安全性。

鐵砧山構造為一完整封閉背斜構造，其深部地層曾蘊含豐富天然氣，歷經50餘年開採後逐漸轉作為天然地下儲氣窖之用。經評估鐵砧山背斜構造之淺部地層適合作為碳封存，桂竹林層中砂岩厚度足夠、孔隙率及滲透率良好、深度適中，有利於封存二氧化碳，上覆蓋層錦水頁岩層緻密且厚實，可有效將二氧化碳阻隔而不洩漏。

經地質建模及數值模擬研究，在鐵砧山碳封存示範計畫場址灌注二氧化碳後，二氧化碳將聚積於所在之構造局部高區上。以年灌注10萬噸二氧化碳，持續3年累計共30萬噸條件下，停注後100年，二氧化碳團塊範圍分布距灌注井最遠約為600公尺。

中油公司預計於2025年啟動灌注封存，目前正著手進行示範場域建置工作，包含於自有廠區內鑽鑿1口灌注井，並且建置相關地面灌注設備，以及利用鄰近2口既有井修井轉為監測井。另外為驗證二氧化碳移棲路徑及團塊範圍，將進行三維震波測勘、灌注井及監測井井下電測，且嚴密監控大氣二氧化碳濃度、土壤氣體、地下水成分、地表變形及微震活動度等，以確保安全無虞。目前調查及監測分析工作已開始陸續進行，以取得灌注前背景基線數據。

鐵砧山碳封存示範計畫將進行小規模灌注封存二氧化碳，本計畫之推動進程、執行經驗與實際監測數據，除可作為其他案場資料蒐集與研究之基礎外，也可供主管機關作為訂定碳封存相關法規之參考。

放射性核種銫對台灣不同母岩吸附特性調查:分配係數研究

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摘　要

本研究利用 ASTM 批次吸附法，針對放射性核種銫（Cs）對於台灣不同地區結晶岩(花崗岩)之吸附行為，進行銫（Cs）在不同地區結晶岩材料中的分配係數探討。由於核能的運用伴隨的是放射性廢棄物的產生，放射性廢棄物處置場的建置將是未來我們將必要面對的重要工作；一般咸以「多重障壁」的概念，做為放射性廢棄物處置場的設計，亦即利用天然岩層的隔離阻絕特性，配合人工的包封容器、緩衝回填材料及工程設計所形成的多重屏障系統，有效地使外釋而遷移的放射性核種受到隔離與阻絕的效果，藉以換取足夠的時間，使放射性廢棄物的輻射，在影響人類生活環境之前，已衰變至可忽略的程度。

從批次實驗結果顯示,不同地區的花崗岩對銫(Cs)的吸附率平均約 5-10%。XRD 分析結果顯示，發現花崗岩中含有石英、長石、雲母等礦物成分，除了應用批次吸附實驗以外、並以掃描電子顯微鏡與 X 光螢光分析（XRF）固相分析技術,瞭解經吸附作用行為後,礦物相晶體結構的變化與表面元素化學狀態的訊息,進而分析瞭解吸附作用的物化行為機制。

關鍵字：吸附、銫（Cs）、結晶岩、放射性廢棄物、處置場

二氧化碳深地質鹽水層之物理及化學封存：非均質構造下的二氧化碳移棲行為

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摘　要

大尺度的碳捕捉與封存 (Carbon Capture and Storage, CCS)是達到2050淨零碳排的必要手段之一。然而將二氧化碳灌注到地底後，注入地層的孔隙率、滲透率、毛細壓力等物理量的局部變化會大幅影響二氧化碳在地層中的行為，因此，考慮儲集層以及周遭地層的非均質性十分重要。另外，地層中溶於水的二氧化碳跟其他離子反應後，可以形成礦物或轉換成不溶於水的其他離子，這些被稱為化學封存，也是目前認定最永久的封存方法。

本次研究中，利用知名多相流模擬軟體TOUGH以及TOUGHREACT之ECO2N模組，分別模擬二氧化碳灌注後之移棲、溶解與礦物沉澱等行為。進行模擬的大尺度地質概念模型，地質分層包含含水層、蓋層以及儲集層。以這個模型為基礎，個別設定孔隙率、滲透率、相對滲透率以及毛細壓力的異質性，對以上幾種性質進行模擬與敏感度分析，了解各項物理性質之異質性對二氧化碳遷移和壓力改變中扮演的角色。前述工作著重於二氧化碳灌注後，長時間尺度之移棲作用，本研究第二階段欲以相同地質概念模型假設，增加考慮物理性及化學性封存手段，探討地質特性與相應牽涉的地球化學條件對深層地質之二氧化碳封存儲量的影響。

藉由概念模型探討，建立整套前後處理與核心分析流程，可應用於後續更為複雜的場址尺度，協助加速二氧化碳封存之淨零腳步。本研究將呈現以下初步成果：(1)確立各種物理性質及異質性對二氧化碳灌注的影響。(2)分析灌注後各種異質性模型中壓力和飽和度分布。(3)評估此模型下物理及化學封存分別的碳儲量。

關鍵字：數值模擬、非均質性、二氧化碳封存、淨零碳排、

Integrated Risk Analysis on CCS Site Screening Using Play Chance Mapping

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Abstract:

For a Carbon Capture and Storage (CCS) site to be considered feasible, it must not only possess appropriate geological conditions but also satisfy various non-technical requirements. The screening process of a suitable CCS site encompasses a comprehensive risk assessment, combining knowledge and data from multiple domains. This abstract illustrates the application of the play chance mapping approach for evaluating both technical and non-technical risks associated with potential CCS sites in Petrel. This method facilitates the conversion and integration of geological parameters into interpretable risk maps.

The workflow introduces customized risk criteria for different risk elements, converting geological information into a series of risk maps. These maps are then aggregated by multiplication, generating a comprehensive risk overview for the area under consideration. This systematic approach allows geologists to consolidate all existing regional knowledge and data, pinpointing the most appropriate CCS site characterized by minimal geological risks.

Keywords: Carbon capture and storage, CCS site screening, risk assessment, play chance mapping, Petrel

以卡爾曼濾波與主成分分析探討 GPS 時間序列中的暫態變形訊號

Transient Deformation of GPS Time Series from Kalman Filtering and Principal Component Analysis

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摘要

GPS 位移時間序列中所含的暫態訊號可以反映地表諸多變形，如震後位移、火山作用及地下水位變化等，讓我們能夠以此研究地殼變形的性質並洞察災害發生的可能性。但在此連續位移紀錄中，存在著非常多的雜訊，導致較微弱的暫態訊號因低訊噪比而較難被觀察到。本研究參考 Ji and Herring (2013a)所提出的方法，將 FOGM (first order Gauss-Markov)隨機過程置入原始時間序列的狀態函數中，並以卡爾曼濾波器(Kalman filter)去除序列中固定振幅的趨勢(trend)、年週期、半年週期等狀態訊號以及白雜訊(white noise)，其所得的 FOGM 過程即包含了序列中各狀態分量的動態變化以及色雜訊(color noise)。最後將各站各分量的 FOGM 進行主成份分析(principal component analysis, or PCA)，以萃取其在時間與空間中的主要共同分量。相較於色雜訊，GPS 測網中顯著的共同暫態地殼變形多來自位移趨勢中低頻且振幅較高的變化，因此將預期出現在 PCA 前面的幾項主成份。此方法可同時降低雜訊在時間域及空間域的影響，使微弱的暫態訊號能夠更容易被檢測。我們將以位於美國西部 Utah 州 Wasatch 斷層帶的 GPS 測網資料作為範例(觀測時間>10 年)，分析此區域可能出現的暫態地表變形以及它們與此斷層的關聯。

Spatial variation of effective elastic thickness in Northwestern South America

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Abstract

Northwestern South America has a complex tectonic setting where Nazca, Caribbean and South American plates converge. Furthermore, this area is characterized by a high seismic activity and volcanic activity. An important parameter to better understand the mechanical strength of the lithosphere and its resistance to the deformation is the effective elastic thickness (Te). The Te of the lithosphere is the thickness of an elastic layer that responds to long-term geological loads and therefore can reflect the deformation mechanism. Making use of Bouguer anomaly extracted from WGM2012 gravity model and topography data from ETOPO1, a spatial variation of the Te is obtained for this area. A joint inversion of admittance and coherence is calculated using spectral methods (Morlet wavelet). This joint inversion yielded Te values ranging from 20 to 50 km, with high values up to 70 km in the Amazon Craton and a subsurface-to- surface loading (F) of 0.2, which imply a dominant surface loading in the area. There is an apparent relationship between high Te values and high S wave velocities, however a connection between Te and heat flow values has not been identified. Additional analysis is needed to determine if there exists a link between Te and seismogenic thickness.

Keywords: South America, Bouguer Anomaly, Wavelet, Admittance, Coherence

以多時序 InSAR 分析軟弱土層分布致使之都會地區地表沉降：以臺北市大直地區為例

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摘　要

2023 年 9 月發生於臺北市大直地區發生的建物倒塌事件，引起公眾對於都會地區內結構物穩定性的擔憂。為了探討與此事件相關的促成因素，先進的遙測技術可以提供廣範圍的調查分析結果。近年來，多時序 InSAR 被廣泛應用以提供都會地區地表變形的空間與時間特性。在本研究中，亦將應用多時序 InSAR 分析技術，探討分析在建物倒塌事件前大直地區的變形特徵。在 2023 年以前的長期 InSAR 觀測成果顯示，一個長期的局部沉降熱區包含了大直建物倒塌的所在街區，此發現揭示了此區域內建物的潛在風險。本研究應用小基線法(Small Baseline Subset)進行一年期的多時序 InSAR 分析，在研究成果中顯示大直地區的平均下陷速率可達每年 20 毫米。此一持續下陷的現象代表此區域存在誘發局部地表持續沉降的因子，造成大直地區發生集中於街區而非盆地尺度的地表沉降風險。根據臺北盆地內的鑽井資料，在大直地區地表下細粒料含量超過 60%的土層厚度超過了 25 公尺，此種軟弱土層的分布推測為地表沉降的主要因子。與臺北市的古地圖相互比對之結果顯示，現在大直地區存在一處古湖泊，且此古湖泊分布範圍與軟弱土層的分布吻合，古湖泊所在區域形成了大直地區的地表沉降中心。此案例顯示長期多時序 InSAR 對於區域性災害監測的潛力，在都會區進行廣範圍的 InSAR 觀測與分析，能主動偵測潛在的地表沉降熱區，以利後續災害應變與公共安全評估。

關鍵字：多時序 InSAR，地表沉降，大直倒塌事件

宜花地區活動構造與地質分區的探討：以 GNSS 速度場資料及聚類分析方法為基礎

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摘　要

宜蘭花蓮地區位於臺灣地區板塊的碰撞帶，菲律賓海板塊朝北與西北方向，分別隱沒於琉球弧溝系統與歐亞大陸板塊下，是個地震活動最為頻繁，地質構造最為複雜的地區。由於受到板塊運動與地體構造的影響，在地表上呈現出不同的地殼變形與構造活動。

聚類分析是一種精簡資料的方法，透過非監督(unsupervised)的方式，依據樣本之間的共同屬性，將比較相似的樣本聚集在一起，形成叢集(cluster)。常見以距離作為演算的依據，相對距離愈近，相似程度愈高，分群之後可以使得群內差異小、群間差異大。

GNSS速度場資料係依據各站點長期的觀測，分析獲得的地表變動趨勢，代表著該位置的空間變異特性，可以反映出地殼變動與構造活動的影響性，藉此了解區域內是否有顯著的地表變形差異，客觀的獲取不同的地質分區。

本研究分別採用K-mean與K-medoids分群演算法，針對三維速度場的變化趨勢，測試僅靠水平速度場，或是增加了垂直速度場後，對於分群演算方法與應用二維或三維資料對分析成果的影響。並嘗試將叢集與叢集邊界，與前人對臺灣地質分區及活動構造相關研究進行對比，藉此驗證聚類分析方法的可用性。

關鍵字：活動構造;地質分區;速度場;聚類分析

Investigation of Active Tectonic and Geologic Province in the Yilan-Hualien Region: Based on GNSS Velocity Field Data and Clustering Analysis Methods

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Abstract

The Yilan-Hualien area is located in the tectonic collision zone of the Taiwan. The Philippine Sea plate faces north and northwest, and is subducted under the Ryukyu arc trench system and the Eurasian continental plate respectively. It is an area with the most frequent seismic activity and the most complex geological structure. Due to the influence of plate movement and tectonics, different crustal deformations and tectonic activities appear on the surface.

Cluster analysis is a method of streamlining data. In an unsupervised manner, relatively similar samples are gathered together to form a cluster based on the common attributes between the samples. It is common to use distance as the basis for calculation. The closer the relative distance, the higher the degree of similarity. After grouping, the differences within the groups can be small and the differences between groups can be large.

GNSS velocity field data is based on long-term observations at various stations and analyzes the surface movement trends. It represents the spatial variation characteristics of the location and can reflect the influence of crustal changes and tectonic activities, thereby understanding whether there are significant changes in the area. The differences in surface deformation can objectively obtain different geological divisions.

This study uses K-mean and K-medoids grouping algorithms respectively. Aiming at the changing of the three-dimensional velocity field, the test relies only on the horizontal velocity field or adds the vertical velocity field. For the grouping algorithm method and application of two-dimensional or three-dimensional data impact on analysis results. We also tried to compare clusters and cluster boundaries with previous studies on geological province and active tectonic in Taiwan to verify the usability of the cluster analysis method.

Keywords: active tectonic; geologic province; GNSS field velocity; clustering analysis

Present-day to Millennial Timescale Plate Kinematics of Mountain Building Across Taiwan

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Understanding slip rates in active orogens is crucial for understanding mountain-building processes and assessing earthquake hazards. However, previous studies in Taiwan and most mountain belts, globally, rely primarily on horizontal geodetic velocities to estimate slip rates, neglecting the significance of vertical deformation in active orogenic regions. To address this gap, we utilized a 3D lithospheric kinematic plate modeling approach from Johnson et al. (2020) in Taiwan. Unlike the traditional block modeling approach, our plate model combines an elastic upper crust overlying an inviscid lower crust and mantle to incorporate vertical motion through fault slip and associated plate flexure. We employed a Bayesian approach to invert fault slip rates, including strike-slip and dip-slip motions, and interseismic locking distributions on faults constrained by short-term horizontal (GPS), short-term vertical (GPS and leveling), and long-term vertical (rock uplift and river incision) rates. The Monte Carlo-Metropolis sampling algorithm is used to generate a discrete representation of the posterior distribution of these parameters. Our inversion method with the kinematic model identified the distribution of slip rates across the entire Taiwan plate boundary, providing valuable insights into the mechanics of mountain building and earthquake behavior in the Taiwan fold-and-thrust belt. Our model explains the overall pattern of crustal deformation, as evidenced by geodetic and geological data across the fold-and-thrust belt and longitudinal valley suture zone. However, we identify systematic misfits to the geodetic data along with high slip rates compared to geology in the southwestern fold-thrust belt and the longitudinal valley suture zone. We can explain much of the systematic misfit with a model for distributed off-fault deformation. We conclude that present-day deformation in these regions is likely due to a combination of fast slip rate on faults and anelastic off-fault deformation in the crust.

以Sentinal-1影像監測荖濃溪部分河段之土砂變化可行性評估

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摘　要

近年的極端天氣事件(Extreme Weather Event)常造成居民嚴重傷亡，如民國88年九二一地震、民國98年莫拉克颱風、民國101年蘇拉颱風、民國104年蘇迪勒颱風、民國106年0601豪雨及民國110年盧碧颱風街造成嚴重災情；如何有效、即時的監測河道土砂狀態與其時序上的變化，不僅是防減災首要工作，亦為區域治理參考依據。

本研究選取荖濃溪鄰近明霸克露橋河段，以Sentinal-1衛星影像製作DEM，進行民國110至111年間之河道土砂推積變化可行性推估，並以光學無人機所建置之DSM資料進行比對，兩者皆可看出汛期後有明顯土砂推積現象，而若無強降雨事件，河道所堆積之不安定土砂變化不大；本研究評估結果顯示以Sentinal-1所產製之DEM較易有高估與低估之情況，其現象可能來自於鄰近區域植被茂密所影響，然則，廣域且以集水區為單位進行河道不安定土砂之初估與監測實為極端天氣事件下不可避免的重要方向，未來建議可針對該估算方法之精進及廣域監測流程之確立。

應用衛星影像探討龜山島火山活動性

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摘　要

龜山島為歐亞板塊與菲律賓海板塊碰撞而隆起的產物：兩個板塊持續推擠，因為較重的菲律賓海板塊密度較大，每年以7~8cm 向北的速度隱沒至密度較小的歐亞板塊下方，當隱沒帶的岩石深度到達地殼底部之後，板塊相互摩擦生熱，就使岩石的沉積物熔融成岩漿，產生的岩漿其密度較低而向上浮至地表噴發，同時形成一串弧狀排列的火山，包括龜山島在內的台灣北部火山帶，都是屬於琉球島弧向西延伸出來的火山。

本研究為了觀察龜山島的火山活動性，應用Sentinel-3衛星影像監測龜山島周圍海域因為海底火山噴發而改變海水物質的變化，透過海洋與陸地彩色儀器(Ocean and Land Color Instrument，OLCI)，針對龜山島海域中懸浮物及葉綠素進行濃度解析，期望研究結果可得到龜山島海底火山噴發前、後，影響周圍海域懸浮物多寡及海水中葉綠素的變動，驗證火山活動與海水物質變化之相關性。

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淺談 Isca GCM 之全球氣候變化模擬技術應用於用過核子燃料最終處置之安全評估情節發展

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長期氣候變化趨勢及特徵是影響用過核子燃料最終處置於安全評估之情節發展的重要外部條件之一。在考量百萬年尺度之周期，全球暖化、冰期-間冰期的氣候循環特徵等，均可能導致臺灣本島之海平面與地表環境的改變，進而影響地下水循環機制與地表生態系統特性。其中，地下水循環將致使近場之水文地質條件變異，並可能成為放射性核種由處置設施傳輸至生態系統的潛在外釋路徑。而諸多地表環境特徵的變異演化，則影響放射性核種的釋出位置與其對生物圈的影響。

據此，為更瞭解臺灣本島區域受氣候變遷影響的未來變化過程和潛在風險，本研究利用大氣環流模式（GCM）來模擬全球長期氣候循環，並著重於探討冰河循環周期或全球暖化對熱帶與副熱帶地區之影響，進而降尺度至台灣鄰近區域的氣候變化情形探討。另，本研究亦選擇 ISCA（理想化的全球環流建模架構）來模擬長期氣候變化特徵，為檢核氣候參數敏感度與變異性，並探討其在各項經驗公式中的一致性，本研究透過二氧化碳濃度改變情境、地軸傾角和現實海陸分布的配置來調節全球能量配置，藉此瞭解氣候變化的機制，透過情境模擬測試，可具體瞭解不同的氣候情境之未來可能發展及探討其影響，且可作為未來發展用過核子燃料最終處置安全評估之氣候演化研究之依據。

關鍵字：用過核子燃料最終處置；全球氣候模式；氣候變遷

Establishment of a Plastic-Free Laboratory

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ABSTRACT

Plastic products are among the most widely used materials in the world today. However, the substantial increase in plastic production has led to a significant threat to the environment, biodiversity, and even human health, in the form of plastic waste. Plastics can be degraded into smaller plastic particles, known as microplastics. Microplastics are now ubiquitous found in urban areas, water bodies, and even remote forests. Microplastic material embedded in coral skeletons offers a potential means of reconstructing oceanic plastic pollution over past decades. Many experiments conducted in previous studies, particularly those in conventional laboratories, risk contamination from the ambient environment. To accurately study coral-inferred plastic history, a plastic-free laboratory environment is essential. Here, we established a plastic-free laboratory at the Biodiversity Research Center, Academia Sinica. In the initial stage, five 1-liter samples of fresh tap water and also five1-L pure water samples were tested. Throughout the microplastics enrichment experiment utilizing a 0.7 μm-fiber filter, an average of eight pieces of Rayon were observed in 1-L tap water, while no pieces were found in all pure water samples. In the second stage, we examined 30 cubed (1x1x1 cm^3) subsamples of a 3,000-year-old coral fossil, which had been stored in a closet at the Department of Geosciences, National Taiwan University, for several years. We discovered that cubed coral subsamples contained 1 to 8 plastic pieces, ranging in size from 70 to 1400 μm, which were trapped within the porous structure of cubed subsamples. After six cycles of ultrasonication with pure water, no plastic pieces were observed in any tested coral subsamples. This confirms the effectiveness of our plastic-free laboratory setup. Our developed protocol will be applied to coral samples collected from southern Taiwan and the South China Sea to uncover the history of plastic pollution over the past decades.

應用反射光譜技術探討上新世西太平洋的氣候變遷

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摘要

上新世是全球地理分布、太陽照射強度及大氣中二氧化碳濃度等外營力都與現代相似的時期。藉由增加對上新世氣候的理解，將有助於預測未來的氣候變化。臺灣西南部的古亭坑層為過去南海沉積物經造山運動抬升而形成，亦是臺灣通過深層鑽探探索中最具有生產力的油氣藏之一，該地層為瞭解上新世時期沉積物中生物源組成變化的絕佳材料，為過去西太平洋氣候變遷如碳循環、海洋生產力及洋流和季風模式的變化提供線索。生物源組成如總有機碳（Total Organic Carbon, TOC）、碳酸鈣（$CaCO_3$）的含量可能反映當時的生物生產力、溫度和降雨等因素，重建地層中 TOC 與 $CaCO_3$ 的含量變化有助於瞭解過去碳循環的情況。本研究基於二仁溪古亭坑層露頭與南海北部岩心重建上新世 TOC 和 $CaCO_3$ 組分變化，整合前人研究之相關古氣候代用指標（如黏土礦物、氧同位素），探討上新世西太平洋的氣候變遷。實測 TOC 與 $CaCO_3$ 含量需經過多重耗時費力的步驟，前人研究顯示應用反射光譜估算沉積岩心中的 TOC 與 $CaCO_3$ 含量可大幅縮減時間成本，本研究測量古亭坑層泥質沉積物樣本反射光譜，將光譜數據轉換為 CIELAB 色彩空間之 L*、a*、b*值，同時分析海洋鑽探計畫 (Ocean Drilling Program, ODP）過去在南海北坡取得的沉積岩心之 L*、a*、b*光譜數據，定量沉積物中的 TOC 與 $CaCO_3$。預計這項研究將有助於識別古亭坑層沉積物的生物沉積物組分變化，以及與上新世期間南海北坡區域碳循環、海洋生產力及洋流和季風變化模式的整體關聯。

關鍵字: 上新世、反射光譜、古亭坑層、南海、總有機碳、碳酸鈣

Beyond stream power: the dominance of landsliding on the active Taiwan orogen

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Fluvial bedrock incision, which creates topographic relief and influences hillslope stability, has been considered the key process linking denudation and tectonic uplift in non-glaciated mountains. However, taking the Taiwan orogen as an example, this study argues that landslides can dominate over river incision in governing the erosion of active mountains. The Taiwan orogen, reaching 3000 – 4000 m in elevation, is prone to landsliding triggered by heavy rains or large earthquakes. It is shown in the orogen that landslides could drive catchment expansion and bedrock-river avulsion. Also, by determining the yield/caliber of bedload sediment, landslides have controlled river incision/deposition processes and, thus, the morphology of bedrock rivers (width, gradient, sinuosity, and shape of longitudinal profiles). The significant spatial/temporal diversities in landslide sequences, with various magnitudes/ frequencies, then account for: (1) the occurrence of tributaries that are atypically wider or gentler than the trunk rivers; (2) the wide ranges of bedrock incision rates (ranging from zero to several centimeters per year) over different time spans; (3) the contrasts in terrace sequences (and thus river evolutionary histories) among catchments; (4) the differential bedrock incision along rivers, leading to the creation of knickpoints (including waterfalls). All the observations above challenge the applicability of stream power law (assuming the drive of river incision by hydraulic power) in modeling bedrock river incision in the Taiwan orogen. We further find that the activities of landslides around the major drainage divides > 3000 m in elevation have been much lower than the activities of landslides in the mid-elevation regions (perhaps due to the lower seismicity in the high mountains). Given this and the commonness of low-relief surfaces stranded on the major drainage divides, it is unlikely that erosion of the orogen has offset the tectonic uplift. We believe that the elevation of the orogen has been increasing and it is the glacial erosion that can balance the tectonic uplift in the future.

<Key words> Landslide; Fluvial bedrock incision; stream power law; low-relief surface; Taiwan orogen

高頻大地電磁法於長良農場之初步研究
Preliminary study of high-frequency magnetotelluric method at Changliang farm

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摘　要

位於菲律賓海板塊與歐亞板塊聚合帶上的台灣，伴隨著許多的地震事件，且存在著有許多的活動斷層。近年來，隨著國人對災害防治的重視，因此地震防災與減災的工作在國土規劃與經濟建設上越來越顯得其具重要性。

2022年9月18日的池上地震造成春日至池上間產生多處的地表破裂現象，此次地震沿著玉里斷層的地表破裂位置，大部分地區與1951年11月25日台東地震所造成的玉里斷層活動的地表破裂位置相當接近。然而，2022年池上地震在長良地區所造成的地表破裂位置，在1951年台東地震其間卻未具有地表破裂的紀錄報導。因此，本研究為了解長良地區地下地質的狀況，以提供對於縱谷地區地下地質模式的相關研究所參考，用以建立斷層的破裂模式來評估地震災害的防災工作。由於以農地為主的長良農場，對音頻大地電磁法的干擾少，故本研究規劃以音頻大地電磁法的測勘來進行地下地質的調查工作。

利用AVO分析不同地質特徵之油氣潛能

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摘　要

振幅隨支距變化（amplitude versus offset, AVO）分析技術為油氣探勘中常用來尋找油氣的一種方式。在不同地質條件下，震測訊號會因為地層含油氣特性而反映出AVO異常。儘管近年來多以震波逆推技術瞭解地層中岩性與流體特性與分布，但在無鑽井的情況下，AVO仍為一簡單常用的檢測工具。本研究利用一組三維震測的聚排（gather）資料分析三種不同地質條件下的AVO特性，確認是否有AVO異常與其異常類型，並透過AVO的特性快速找出油氣相關訊號的空間分布。首先確認目標區在某一位置的同反射點聚排剖面的深度，以此深度觀察振幅隨支距的變化，用Shuey二項式擬合AVO資料點，得到截距與斜率，再由截距與斜率關係圖區分AVO異常類型，最後找出AVO異常在空間上的分布。本研究分析三種不同的地質特徵，分別為濁流砂體、海底仿擬反射與斷層強振幅訊號，分析結果可確認是否為AVO異常，和其與岩性或流體的關係。本技術可釐清強振幅訊號的油氣潛能，作為後續油氣探勘參考。

關鍵詞： AVO異常、海底仿擬反射、濁流砂體

探尋沉睡的歷史－於台江水域透過無人機磁測技術進行水下文資探勘

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摘　要

西元 16 世紀，台灣歷經荷蘭與明鄭時期的更替，大量的船隻於現今的台江水域來往頻繁，1661 年，鄭成功挾戰船數百艘開往台灣南部鹿耳門，於一年之間與荷蘭人交戰數次，最終驅逐荷蘭人，開啟 21 年的鄭氏統治時期。此數番交戰，兩方多艘戰船沉沒台江水域，歷經三百多年的河流沖積覆蓋，過往的台江水域現今已覆蓋大片的沖積扇平原，而那些承載著數百年歷史的沉船，亦被深埋在數十米的覆土之下。

探索地底下未知之事物，乃是地球物理探勘的優勢，本團隊透過在台灣發展多年的有人直升機中磁測之技術作為基礎，以開發無人機空中磁測之技術。無人機磁測技術，可將探測的範圍再限縮，並大幅度提升測線密度及降低探測高度，以提高資料解析度至公尺級，技術發展至此，探尋地底帶有磁性物質之沉船的可能性便大幅提高。

透過空中磁力探測技術，探尋水下文資為全台首例，本研究在台南台江水域一帶，藉由文獻研究規劃探測區域，於三年間完成台江水域的磁力探測，並逐年提高探測品質，及加深技術之能量，於最後一期之探測結果中亦獲取相當豐碩的成果。

Keyword：空中磁測

透地雷達與管線探測器應用於地下管線調查案例研究

鍾陳東、韓為中、沈顯全
台灣中油股份有限公司探採研究所

摘　要

地球物理探勘利用儀器在地表進行非破壞性探測，如磁力、重力、電磁或震波測勘等方法。透地雷達探測技術在地表對地下發射一種高頻電磁波，當地下物的介電常數發生變化時，電磁波產生反射現象而被地表所接收，由累積接收的反射訊號可分析解釋地下物的形貌與材料特性等，依照探測天線頻率之高低不同，分別可應用於鋼筋、橋面板、混凝土裂縫、管線、空洞、地層層位、水中沉積物與考古等調查工作。管線探測器則利用電磁感應方法，探測交流電持續變化產生之電磁場，並藉由感測訊號強度，推測管線之位置與埋設深度。

本研究分別應用透地雷達探測與管線探測器技術，針對同一場址進行地下管線調查，以瞭解場址之地下管線分布情況。其中，透地雷達資料經過零點修正、背景移除、濾波和移位等資料處理後，得出地下雷達剖面圖，並藉由反射訊號在剖面上的形態特徵來判識管線。管線探測器則採用主動探測模式，將發射器連接場址出露之金屬管頭，再利用接收器以S型路徑探測，以瞭解此出露管線之地下分布情況。

研究成果顯示透地雷達與管線探測器皆有探測出出露之金屬管線路徑，且兩者探測之深度差異不大。同時，透地雷達於場址內還探測出其他數條未知管線及掩埋之人孔蓋。在進行現場有出露管線之地下管線調查時，除了使用管線探測器外，在預算與時間允許下，建議進行透地雷達探測，方能確認場址內所有地下管線分布。摘要內容

中文關鍵字：透地雷達、地球物理探勘、非破壞性檢測、管線調查
英文關鍵字：Ground Penetrating Radar、Geophysical Survey、 Non-destructive Testing、Utility Locating

地雷達應用於開挖場址之地下環境調查

Investigating underground Structure of Excavation Sites by Ground Penetrating Radar

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摘要

開挖施工誤觸管線釀災事件頻傳，若能於施工前掌握地下管線分布位置，可避免許多意外。透地雷達為一種非破壞性探測技術，在開挖前先探測地下管線的位置與深度，搭配既有的圖資，可提高開挖工程的安全性與效率。本公司於例行IP管線檢測作業時，管內檢測設備意外卡在地下管線中，經評估後需開挖路面並截切該段管串以取出設備，然而開挖區域位於某石化工廠內，地下管線密集且該處鄰近化學槽與管架橋墩，僅憑既有的圖資與現場人員的說法，難保不會誤挖埋於地下之結構物與管線，為瞭解卡管發生管段附近之地下環境，故以透地雷達對預計開挖區域進行地下環境探測，本次調查作業使用400MHz單頻透地雷達進行施測，共佈設6條垂直於管線走向之測線。透地雷達資料經時深轉換、零點修正、濾波處理、訊號增益等資料處理後，進行地下管線與異常特徵之判釋和分析，由剖面中可發現，該區域植草磚下層為鋼筋鋪面，於深度約0.5公尺至0.65公尺處有4個管線訊號，目標管串應為其中之一。後續開挖作業參考本次探測之管線與結構物判釋結果進行，於地下發現5條管線，深度為0.5公尺左右，與透地雷達探測結果大致吻合。

關鍵詞：透地雷達、土木工程、地下管線、GPR、Ground Penetrating Radar、Pipeline、Civil Engineering

非洲 M 構造儲油層三維地質模型更新

Update of 3D Geological Model of M structure reservoir, Africa

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隨著油田邁入生產開發階段，油田基礎資料日趨豐富，利用既有數據資料建立儲集層三維地質模型已成為必要工作項目之一。無論大至構造框架，或精細賦予儲集層內各網格內的屬性，皆需要透過建模工作整合地下儲層的空間（連續性或非均向性）分布特徵。故三維地質模型的建立與更新可謂奠定後續生產開發工程規畫的基礎。

非洲 M 構造區塊過去曾以地質統計學震波逆推方法（Stochastic Inversion）完成地質建模。本研究利用新取得之鑽井地層分層資料，更新主要儲油層地層頂部與斷層構造解釋，並嘗試以不同震測資料 體（PSDM 深度域）進行構造建模。在屬性建模方面，則利用十多口已鑽井電測計算出的岩石物理參數結果，以地質統計學（Geostatistics）方法模擬其空間機率分布，其中岩相（Lithofacies）屬性採用序貫指示模擬法（Sequential Indicator Simulation, SIS），而砂頁岩比、孔隙率、含水飽和率等岩石物理屬性則採用高斯自由函數模擬法（Gaussian Random Function Simulation, GRFS），透過體積百分比統計及變差函數（Variogram）等地質統計演算法分析過程，進行各屬性於三維空間中的機率分佈特徵模擬，最後完成 M 構造儲油層之地質構造與屬性模型更新。

由於隨機模擬必定存在不準確性，本研究亦調整相關參數進行 50 組原油現地埋藏量的推算，完成此模型的不確定性分析。相比 2021-2022 年採用的模型，本模型所推估的原油現地埋藏量在儲層上半段較大、在儲層下半段則較為保守，分析之後推測構造模型的差異應是主要差異來源。後續模型若再更新時，宜討論 M 構造儲集層頂部深度位置，並加入砂體沉積模式分析控制，使儲層地質模型更加精細化，且符合生產模擬結果。

關鍵詞：地質模型、地質統計學、儲層特徵
Keywords：Geological Modeling, Geostatistics, Reservoir Characterization

嘉南-花東山區空中重力探測初步成果

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摘　要

重力測勘量測在空間中因地下不同密度岩石造成的重力加速度差異，進而推估地下地質構造，常用於礦產資源調查及區域地質構造調查等。臺灣島約 2/3 為山區地形，地形崎嶇陡峭使地表調查相當困難。空中重力調查具備快速、不受人為設施及地形限制的特點，適合進行大區域地質構造調查。空中重力雖具備許多好處，但由於地質構造產生的重力異常值遠小於飛行載具震動、移動造成的重力值改變量，如何從雜亂無章的量測資料中擷取出具備地質構造意義的信號，是空中重力資料處理的一大挑戰。

2021 年經濟部中央地質調查所(現改制為經濟部地質調查及礦業管理中心)引進空中重力探測設備，並於 2022 年在花東縱谷中部的池上、南橫公路地區，以直升機為載具、類地貌飛行方式進行小區域空中重力探勘測試，分析空中重力測勘的資料特性及探測限制，初步確認利用直升機為載具在臺灣地區進行空中重力探測的可行性。

本研究依據 2022 年對空中重力探測試驗，掌握空中重力探測的特性及作業缺點，修正野外作業方式，進行較大範圍的空中重力探測。測區範圍包括南投、嘉義、台南、高雄、花蓮及臺東等縣市，測線橫跨中央山脈、航行高度自 1500 公尺~4500 公尺，計完成面積達 3000 平方公里空中重力探測。初步比較本研究與前人利用定翼機飛行的自由空間異常，兩者大趨勢一致；本研究由於測線間距較小、飛航高度低、更貼近探測目標，能提供較過去更多資訊，資料處理仍持續進行中。

關鍵字：空中重力、區域地質構造、中央山脈

七星山西北麓地區近地表熱液初步探查

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摘　要

陽明山國家公園是台灣唯一擁有火山自然景觀的國家公園。自 1970 年代開始，陽明山地區進行了許多地球科學研究調查，以收集有關地質、礦物、熱液溫度等地下資訊。整合大屯火山群過去的地質、地球物理和地球化學的研究成果，大屯火山群已被認定為一座活火山，其明顯的火山活動和噴發潛勢，可能導致嚴重的地質災害。因此，進行勘查和監測熱液活動及潛在噴發路徑的工作是必要的。

根據前人研究指出，大屯火山群的後期噴發主要是以蒸氣噴發為主，七星山蒸氣型噴發是屬於地下有熱液儲集層、累積氣體壓力後噴發形成。這暗示其中存在幾項重要特徵：火山流體上升、存在地下水且被加熱以及存在黏土質蓋層，當累積的壓力超過黏土質蓋層的強度就發生蒸氣型噴發。而地電探勘方法對於地層中的含水區域、導電物質和構造變化具有極高的敏感度，適用於探勘地下熱液活動與潛在噴發路徑。

本計畫使用對於近地表探測能力佳的地電阻影像法（Electrical Resistivity Tomography, ERT）在地形條件許可的區域內進行探測，完成 6 條 ERT 測線，初步探查七星山西北麓地區的淺部地下電性構造，嘗試推估地下熱液、導電礦物（例如硫磺）與裂隙的分布情況。過去許多國外火山地區研究，已證實地電阻影像法之分析方法與解析能力，適用於火山地區近地表的探勘研究。本計畫之觀測結果，可用於配合不同的地球物理、地球化學、地質學等領域之分析數據交互驗證，並協助政府相關部門和學術機構進行火山活動評估與制定應對潛在災害的對策，保護周邊居民和遊客的生命財產安全。

從電性構造模型結果中判釋七星池地區可能存在古老的噴發通道，其位置主要在七星池上池與下池，推測至少向地下延伸超過 30 公尺。小油坑爆裂口也觀測到向地下延伸的低電阻異常區，應與噴發通道有關。在噴氣活動強烈的小油坑爆裂口附近，存在極低（低於 1Ωm）的低電阻率異常區，此現象與過去大油坑研究結果一致。但在七星池地區並不存在低於 10Ωm 的電阻率異常。整理過去研究可發現，活動中的噴發通道附近常見存在大量的導電礦物，隨著噴氣活動度降低，導電礦物比例下降，電阻率也提升。七星山地區的極低電阻異常區主要成因是大量的導電礦物，而導電礦物的分布範圍必然與熱水、裂隙、噴發活動有密切的關係。

利用非線性動態稀疏識別法建立電離層TEC模型

Establishing an ionospheric Total Electron Content (TEC model using sparse identification of nonlinear dynamics method.

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摘　要

根據電離層物理理論，科學家利用已知參數建立電離層模式以模擬電離層電漿濃度的變化，但是仍有許多未知或沒有考量到的參數，因此時常出現預報不準確的情況。

本研究嘗試利用非線性動態稀疏識別法(The sparse identification of nonlinear dynamics method，簡稱為 SINDy 法)，透過分析電離層全電子含量(Total electron content, TEC)參數以及電離層中不同的參數變化，反推電離層動態系統的非線性運動方程式。本研究進一步與現有的公式(電離層電漿連續方程式)進行比較，評估和修正 SINDy 法所反推的公式中各個函數的種類、各個參數的權重，並判斷其是否為合理的方程式與探討其與現有的公式的差異。

關鍵字：非線性動態稀疏識別法、全電子含量、電離層模型

Abstract

Based on ionospheric physics theories, scientists establish ionospheric models using known parameters to simulate variations in ionospheric plasma density. However, many parameters remain unknown or are not considered, leading to frequently inaccurate forecasts.

This study attempts to utilize the Sparse Identification of Nonlinear Dynamics (SINDy) method to analyze Total Electron Content (TEC) parameters and variations in different ionospheric parameters, in order to infer the nonlinear motion equations of the ionospheric dynamic system. Furthermore, this research compares, evaluates, and adjusts the functions and weights of parameters in the equations inferred by the SINDy method with existing formulas (ionospheric plasma continuity equation), determining whether they are reasonable equations and discussing differences with existing formulas.

Keywords：Sparse Identification of Nonlinear Dynamics、Total Electron Content、Ionospheric Model

透過深度學習判斷 P 波初動極性及其在震源機制反演中之應用

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摘 要

本研究探討深度學習技術在地震學領域的應用，特別聚焦於 P 波初動極性的判斷以及其在震源機制解反演中的實際應用。震源機制解提供斷層的幾何型態和機制的訊息，有助於深入理解震源的破裂過程和區域應力場特徵。在地震頻繁的台灣，及時獲取地震資訊對於救災和降低地震所帶來的損失極為重要。決定震源機制解的傳統方法可分為波型擬合和 P 波初動法兩類，分別適用於中強地震和小地震。對於 P 波初動法，以往是透過測站接收到的 p 波判斷初動的極性。然而，隨著地震網的迅速發展，仰賴人工判斷的方式判別，已難以應對龐大數據的處理需求，滿足地震監測發展的需求，因此這類任務越來越多地由自動化演算法承擔。

近年來，深度學習技術在自然語言處理和圖像辨識的任務中得到廣泛運用，同時在地震學領域的應用也展現出卓越的能力及潛力。P 波初動極性通常被劃分為上動、下動及不確定三類，可被視為分類的任務，通過大量的已知標籤進行監督式學習。本研究將採用深度學習技術，著重於提高 P 波初動極性判斷的效率及準確性。具體而言，將以已知震源機制解的數據做為訓練集，使用 P 波到時之垂直加速度訊號作為輸入資料進行訓練。經由模型判斷的 P 波初動極性後，並結合三維速度模型所求得之方位角及離源角，解算出震源機制解。此方法的優勢在於自動學習特徵和模式的能力，無需繁複的手動提取過程。同時，有效的處理波型特徵的複雜性，從而提高判斷的精確性。更重要的是，能夠快速且精確地反演出震源機制解。未來將進一步探討不同區域的地震測試模型的表現，期望在地震發生時，能夠迅速且準確地解算出震源機制初動解，獲得震源在不同方向上的強度和能量分布情況，為災害應應變提供關鍵性的支援。

關鍵字 : 震源機制解、P 波初動法、深度學習

應用震波屬性及類神經網路識別泥貫入體之可行性研究

Feasibility study on applying Seismic Attributes and Neural Network to identify Mud Diapir

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以往於台灣西南海域海床下發現許多泥貫入體分布，由於泥貫入體與地層之界面與鹽貫入體不同，缺乏明顯之反射界面，且其形貌與褶皺接近，主要根據泥貫入體內部呈現無反射訊號或渾沌相之特徵，藉由人工判釋地層反射訊號之有無，圈繪出其位置。目前已發展出許多震波屬性用來輔助識別地層特徵，亦有借助多重震波屬性及類神經網路進行斷層及氣囪識別之研究。本研究藉由結合不同的震波屬性，利用商業軟體的類神經網路分析工具對震測影像進行分類，嘗試分類出不同震測特徵之區域，從中識別出泥貫入體之位置。

震測特徵的描述區分為反射振幅、反射連續性及反射頻率等三類，本研究初步依其對應的震波屬性採用均方根振幅(RMS Amplitude)、震測包絡線(Envelope)、方差(Variance)、渾沌(Chaos)、主頻率(Dominant Frequency)及瞬時頻率(Instantaneous Frequency)等，加上原始的震測影像作為類神經網路的輸入資料進行分類。利用人工判釋方式圈繪泥貫入體範圍作為對比來檢驗其分類成果。本研究設定不同的屬性組合及調整參數進行分析，探討對於識別泥貫入體的影響，並尋求適當的操作方式進行影像分類，套用於相同地質環境的震測影像，嘗試識別出泥貫入體的位置並與人工判釋的成果進行對比。

中文關鍵字：震測解釋、震波屬性、類神經網路、泥貫入體

英文關鍵字：Seismic Interpretation, Seismic Attribute, Neural Networks, Mud Diapir

以同步輻射吸收光譜應用於地質材料分析

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摘　要

地球與環境科學是一門橫跨許多不同領域所集合而成的學科，這當中不只是包含了科學，還有產業界和我們日常生活中所涵蓋的知識。在解析一個成因複雜且同時彼此相互牽連的問題，切入此門科學中更需要集合不同領域的角度來探討之。因此，從探討科學的本質上，需要一具備多樣性且更多擴充性的分析手段來幫助描繪此學科中各類現象所呈現的可能機制。同步輻射加速器光源的快速演進，重新定義使用X光光源作為分析手段在各個學科領域的應用性，其中當然也包括了地球與環境科學。在第三代光源因為其提供穩定的高光通量，正式成為一項可普及應用各種學科領域的分析方式，並因為其多樣性和高度的擴充性，在各不同學科中皆有相對應的分析系統。以同步輻射加速器為光源所進行的X光吸收譜分析方法，因其超高光通量之特性可用於地球與環境科學中常見的異質和極低濃度樣品，搭配分析方法中的非破壞性和高解析度特性，可提供此領域中異質性或短程有序和非晶型的物質相對應的物理、化學特性和電子軌域資訊，以助重建樣品的反應序列模型。

中文關鍵字:地質材料; X光吸收光譜; 同步輻射加速器光源
英文關鍵字: Earth Materials; X-ray Absorption Spectroscopy; Synchrotron Radiation

SeisPolar: SeisBlue AI地震資料處理平台的P波初動震源機制解模組

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摘　要

本研究旨在應對密集地震網和地震資料量劇增所帶來的挑戰。延續 SeisBlue 的目標，我們運用深度學習技術，致力於提升地震資料處理的自動化程度和效率。我們設計和訓練以卷積神經網路為基礎的模型 SeisPolar，可準確分類地震連續資料中的初動極性，進而解析地震震源機制。

研究結果顯示，我們的深度學習模型在自動識別地震波初動極性的部分，準確率可達到 85%。在極性三個類別(正,負,無法判斷)的精確度和召回率分別為[87%, 77%, 53%]和[84%, 80%, 54%]。隨後，本研究系統整合 FPFIT 將地震初動極性解析出震源機制解，並採用Kagan 測試方法評估預測結果與真實資料之間的相似性。其研究結果顯示，在震源機制解中，近 70% 的 Kagan 角度小於 40 度，表明預測結果有較高的可靠性。

本研究透過 SeisPolar 深度學習模型分類地震波初動極性，不僅大幅減少人工判讀提升速度上的優勢，在品質上，透過地震波初動極性與震源機制解的兩階段誤差門檻的篩選，獲得高度有效性和可靠性的震源機制解。SeisPolar 作為SeisBlue AI地震資料處理平台中的關鍵模組之一，將持續系統整合與優化。

關鍵字：震源機制解、地震觀測、人工智慧、SeisPolar

Keywords: Focal Mechanism, Seismicity Monitoring, AI, SeisPolar

Thermo-Mechanical Insights into Basin Evolution and Syn-Rift Sedimentation Dynamics

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Abstract

Hydrocarbon reservoirs in rifted sedimentary basins are economically critical and are extensively studied through reflection seismic surveys. These surveys reveal subsurface distribution of stratigraphy, fault-and-fold structures, and deeply-buried crustal blocks. Geothermal gradient also plays an important role in the maturity of hydrocarbon. In this study, we employ the thermo-mechanical model DynEarthSol to dynamically simulate formation of sedimentary basins during continental rifting. The models contain elasto-visco-plastic lithosphere deformation, thermal evolution, isostasy and sediment loading, offering a comprehensive understanding of basin evolution. In DynEarthSol, the geometry of sedimentary basin is mainly controlled by crust rheology, regional strain localization, surface diffusion, base level, and terrigenous sediment flux. Furthermore, information about depositional environments can be also derived, enabling analysis on the temporal and spatial migration of sediment distribution within the basins and chronological sequence of depositional events. A series of reference models with various parameters has been tentatively established with DynEarthSol, and further comparison between reference model and observations (i.e., seismic profiles and well logs) will provide important insights into the geological history and development of rifted sedimentary basins.

壁報發表論文
中華民國地球物理學會與中華民國地質學會113年暨學術研討會
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孔內井測訊號推估技術建立之初探

Preliminary study on the establishment of well-logging signal estimation

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經濟部地質調查及礦業管理中心自99年度起規劃執行臺灣山區地下水資源調查研究計畫及平原區地下水主要補注區補充地質調查案，投入大量孔內水文地質特性調查，已掌握未固結岩層及固結岩層之孔內水文地質調查成果。岩層之地層其膠結程度較佳，多以單次井測方式施作，而在西部臺地及平原區，其地層若為膠結程度較差的砂礫石層所組成，則多採用分段井測方式施作，以取得整孔之量測值。對於膠結較差之地層井測結果雖可透過分段井測完成，仍有部分區段銜接處需進行校正，故為解決此種狀況，本研究嘗試透過迴歸分析建立井下電井測訊號推估之關係式，以建立具有高度代表性之完整孔內水文地質調查資料供水文地質特性評估參考。

本研究於110年至112年在濁水溪沖積扇完成34處補充水文地質鑽探與試驗，本次選取使用之測站為彰化縣芬園鄉之芬園站、彰化縣大村鄉之村東站、彰化縣社頭鄉之山湖站及彰化縣溪州鄉之僑義站，其鑽孔深度分布範圍為150至300公尺，孔位分布於八卦臺地東西側及濁水溪沖積扇北扇之平原區。分析結果顯示，自然伽瑪值於線性關係式有較佳之擬合結果，其推估值與實測值之平均誤差值(average relative error, ARE)介於7.76~8.92%；而不同測距電阻值於指數關係式則有較佳之擬合結果，其推估值與實測值之平均誤差值介於17.87~37.11%；自然電位於二次多項式關係式之擬合結果，其推估值與實測值之平均誤差值介於10.43~14.03%。

關鍵字：井測、孔內訊號推估、迴歸分析
Keywords: well logging, downhole estimation, regression analysis

濁水溪沖積扇及周緣重要補注區內礫石層之地物訊號特徵初探

Geophysical Properties of Gravel Formation in Zhoushui River Alluvial Fan and Peripheral Recharge Area

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全台於110年期間遭受56年來最嚴重的乾旱，除由經濟部水利署全力調水與找水外，經濟部地質調查及礦業管理中心(以下簡稱：地礦中心)亦協助提供富集地下水之潛勢區域，根據過去於山區岩層之調查經驗，以礫石層最具開發潛能，故礫石層區域分布特性及其潛能評估亦為重要研究議題。欲掌握較具規模的地下水資源，山間盆地及麓山帶臺地、丘陵區域及礫石層為首要調查重點，且由於以往對平原地下水區周圍臺地、丘陵含水層之邊界特性及伏流水流量評估瞭解有限，因此地礦中心近年分區規劃完成臺灣中部地下水區之地下水層水文地質特性調查及地下水資源評估工作，綜合整各項調查成果，探討水文地質特性與地下水補注及潛能場址之分布，以因應在全球氣候變遷衝擊下，影響區域水資源供需失衡的情形及洪旱災害，期能降低造成國土資源的沉重負擔，並減少影響民生用水安全之虞。

一般而言，電阻率於區段間的震盪變化則反應地層地層材料的顆粒大小，電阻率較高時，以偏向顆粒較粗的砂或礫石組成。為掌握濁水溪沖積扇北扇之扇頂、扇央與八卦臺地周緣及地層下陷區域等範圍內，礫石之岩性空間分布，本研究統計前述範圍內共計13處場址，於水文地質鑽探與孔內水文地質探勘調查時獲得之礫石層電阻率測錄結果，以界定礫石層於範圍內之岩性分布，有助於判斷地層膠結及釐清水文地質架構與含水層邊界特性。將各範圍內之電阻率統計結果與岩心紀錄比對後，可知於八卦臺地周緣及扇頂區之礫石層岩性主要為中粗礫石，其電阻率分別介於 200 至 400 Ω・m、以及 180 至 250 Ω・m之間；扇央及地層下陷區域之地層岩性主要為砂或泥偶夾細礫石，統計其電阻率分布分別僅介於 70 至 90 Ω・m 、以及70 至 80 Ω・m之間，綜整以上，八卦臺地周緣及濁水溪沖積扇近扇頂區較扇央區及地層下陷區更具地下水補注及潛能之場址分布特性，此結果後續將可提供地下水補注及潛能場址分布相關評估議題參考，相關電阻率分布亦可應用於地電阻探測方法反演算逆推地層真實地電阻率時參考。

關鍵字：地下水補注、電阻率、礫石層

Keywords: Ground Water Recharge, Electrical Resistivity, Gravel Formation

水文地質描述模型建置技術研析—以結晶岩體為假設案例

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摘　要

摘要內容根據臺灣核子燃料最終處置計畫，目前採用深地質處置（Deep Geologic Repository，DGR）概念被認為是國際上最可行的高放射性廢棄物（HLW）長期管理方法。此方法將用過核子燃料深埋在地下300至1000公尺的地層中，並利用工程障壁與天然障壁組合建構多重障壁系統，以實現將用過核子燃料長期隔離於人類生活圈之外的處置目標。然而，若裝有高放射性廢棄物的銅罐損壞，可能導致放射性核種的釋出，進而透過地下水流在母岩中遷移，引發潛在的環境安全問題。因此，充分瞭解裂隙岩體含水層的地下水流行為和水文地質特性，將有助於描述地下處置場址所面臨的環境條件。

本研究選擇以大理岩與片麻岩組成的結晶岩體作為假設案例，進行水文地質場址描述模型(hydrogeological site descriptive model)建置之技術開發研究。本研究除蒐集國內外相關地球物理調查及水文地質調查文獻資料外，並採用室內岩心樣本之氣體滲透率結果，結合研究區域之土壤特性，歸整出假設案例研究範圍之結晶岩體水文地質特性參數，以做為模型之初始條件與邊界條件。雖結晶岩體之地下水流動多屬裂隙主控，然而本研究之假設案例之概念模型尚未納入區域性構造以及裂隙構造帶，因此本研究基於前述之數據成果，將模型區分為風化層、裂隙岩體區以及完整岩體區，並以等效連續孔隙介質來建構模型，設定各分區的水文地質參數，建置初版水文地質概念描述模型，透過地下水流模擬及參數率定後，分析獲得之地下水位模擬值與觀測值誤差介於5公尺以內，顯示本研究之水文地質場址描述模型具備代表性，後續應可提供安全評估與長期穩定性分析使用。

關鍵字: 用過核子燃料、結晶岩、等效連續孔隙介質模型、水文地質場址描述模型

八卦臺地重要地下水區邊界特性研析

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摘　要

台灣西部麓山帶銜接平原區之邊界，跨越了孔隙介質含水層與山區裂隙地下水文系統，在不同的構造環境下有不同的銜接水文地質型態，此重要地質邊界也影響地下水向西部平原的傳輸行為。本研究主要目的為釐清西部麓山區與平原過渡帶間的地下水流動與補注機制，以八卦臺地作為主要調查區域，即濁水溪沖積扇北岸之東側邊界為範圍。研究方法主要應用地球物理聲頻大地電磁方法(AMT)，針對區域內的重要構造線與主要地層單元進行多條或三維分布測點探測，以建立跨越山區與平原區邊界水文地質架構。針對關鍵地下水特徵區，配合地質鑽探井與常流點等相關資訊，以地電阻影像剖面法(RIP)解析八卦臺地東西兩翼深度200-300m之地下地質構造與地層含水狀況。同時在入滲特性方面，本研究使用多頻道電磁方法(EM)探測八卦臺地之淺部崩積層及風化層分布情形。

探測成果顯示，八卦臺地之深部富含水地層以香山段砂岩為主，其低電阻分布受八卦山背斜影響，可分為東翼貓羅溪流域與西翼濁水溪流域，屬地下水分水嶺之特性。而彰化斷層的水文地質特性在南北段並非一致，八卦臺地北段之彰化斷層，於斷層兩側之岩性差異不大，但地層電阻卻具有顯著差異，顯示斷層兩側之地層含水狀態不同，可能與斷層上盤背斜構造形成阻水條件有關。淺部含水地層在東西兩翼皆以火炎山段礫岩為主，具透水條件，且無明顯的阻水層存在。地下水位面深度可由電阻等值線分布型態辨別，山區與平原區過渡帶之地下水位深度有顯著變化，如芬園RIP測線，地下水位深度由西向東逐漸變淺，由臺地區深達100m到臺地邊緣，延伸至平原沖積層地區深度約在70-40m之間。另外，當地下水位面接近地表面時，其出湧位置與地下水位分布受地形與岩性交界所影響。八卦臺地崩積土厚度受地勢及河流沖刷影響，西翼具有較厚之崩積土堆積，厚度約5.4-9m厚，東翼地勢相對平緩，崩積土厚度較薄，約3.6-4.8m。本研究調查成果可進一步加強山區與平原區間的水文地質基本調查數據，可作為邊界過渡帶地下水資源開發之重要參考依據。

整合多種井測資料推估裂隙岩體孔內水力傳導係數之初探—以砂岩為例

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摘　　要

近年來地表地球物理探測技術蓬勃發展且被廣泛應用，而在水文地質特性推估方面，國內外學者運用地層電阻資料來計算地層因子，再建立該因子與水力傳導係數之關係。然而，此方法僅適用於乾淨未含泥的岩層中，而臺灣山區裂隙岩體中普遍存在剪裂泥，這導致僅有極少數岩質純淨的樣本能夠符合該理論，而由過少樣本建立的模型無法推估含泥地層之透水特性，導致模式使用上之限制。因此，本研究嘗試透過整合多種井測資料，建立可同時適用含泥與非含泥地層之水力傳導係數推估模式。

本研究蒐集 91 組砂岩之雙封塞水力試驗資料，每組試驗區段皆為 1.5 公尺，並採用包含自然電位差(SP)、自然伽瑪(NGAM)、地層電阻(SHN、LON、SPR、S-L)、流體導電度之倒數(1/COND)等七種精度為公分級的井測訊號，每種井測訊號取其不同特徵值以對應該區段水力傳導係數之對數(logK)。在模型選擇方面，考慮到深度學習方法在處理複雜條件下的問題上具備卓越的能力，有望協助釐清井測訊號與水力傳導係數間複雜的非線性關係。

首先將資料以 8:2 之比例區分為訓練集與測試集，再採用七個特徵值因子(七種井測訊號之平均值)與二十八個特徵值因子(七種井測訊號之平均值、最大值、最小值與標準差)兩種輸入層模式。其中，七因子模式的訓練集R^2為 0.44，測試集R^2則為 0.20；而二十八因子模式的訓練集R^2可達到 0.69，測試集R^2則可達到 0.47。該結果表明，僅以平均值作為區段代表特徵值較無法建構出訊號與水力傳導係數之關聯度，而納入更多樣特徵值組合有助於優化關聯度，並提升模型準確率。

綜整本研究成果顯示，透過整合多種井測資料並採納多樣化的特徵值，確實有效地提升了模型的準確率，但仍未達到工程上可應用之標準，究其原因，91 筆資料對模型訓練來說仍有樣本數過少之疑慮，而篩選出與地層透水特性更具相關性的特徵值亦是未來可努力之方向。

關鍵詞：井測訊號、裂隙岩體、水力傳導係數、水文地質、深度學習

氫氧同位素估算地下水平均滯留時間影響因子初探

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摘　要

地下水平均滯留時間(Mean Resident Time, MRT)是一個瞭解區域水文很重要的參數，本研究使用位於大屯火山區北麓北磺溪流域2口溫泉監測井(TB-MW-29、TB-MW-30)與降雨，由2021年10月至2023年4月共19個月氧同位素資料，透過大屯火山地區氧同位素季節性變化特性，利用降雨與地下水正弦函數相位差異估算本區地下水平均滯留時間，並與陳(2023)利用一年資料估算結果比較，探討利用氧同位素估算地下水平均滯留時間之影響因子。

初步以原始資料、移動平均以及去極端值方式分別估算，結果顯示以原始資料估算分別為29、59天；移動平均方式估算分別為545、891天，另外，去移除極端值結果分別為806、986天，結果與陳(2023)利用12個月資料估算比對，初步顯示移除極端值對利用氧同位素估算MRT遠比資料長度影響明顯。

關鍵字：平均滯留時間、大屯火山區、氧同位素

以多項式混沌展開法分析離散裂隙網路溶質傳輸不確定性

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摘要

目前我國對用過核子燃料採用的處置概念，遵循世界核能國家普遍採用的深地層處置(deep geological disposal)，並以多重障壁系統(multi-barrier system)以阻絕、延遲核種外釋。若廢料罐不幸遭破壞使核種產生外釋，核種將透過流經破裂廢料罐之地下水於裂隙岩層的離散裂隙網路 (discrete fracture network, DFN)中傳輸，最終抵達人類活動的生物圈(biosphere)。由於 DFN 的裂隙連通性受裂隙參數如位態(orientation)、大小(size)、強度(intensity)和導水係數(transmissivity)等因素影響，故其傳輸行為具有高度不確定性。因此，不確定性分析為場址功能安全性評估的必要步驟。本研究以台灣電力公司公布的 SNFD2017 參考案例的裂隙資料表為參考資料，並使用 dfnWorks 以在 100 m 的立方體模擬區域中產生 DFN，並於模擬區域中釋放 3000 個粒子(particles)模擬核種外釋，分析不同裂隙參數對粒子平均走時的不確定性。不確定性分析方法用稀疏格點配置（sparse grid collocation, SGC）與混沌多項式展開（polynomial chaos expansion, PCE）的數值計算方法替代傳統的蒙地卡羅（Monte Carlo, MC)，計算粒子平均走時的一階、二階以及總敏感度指標。SGC 方法的概念為多個積分張量積組合(tensor product)，比傳統數值積分，SGC 可用較少計算量而有更精確結果; PCE 則採代理模型(surrogate model)概念，將模型以有限個正交多項式(orthogonal polynomial)及係數組合表達，其中係數可用譜投影法(spectral projection)，或者用最小平方法(ordinary least squares)計算。SNFD2017 參考案例中，SGC 方法只能靠提升積分精度，觀察不同精度結果的收斂性得到較可信的結果; PCE 方法則能以 dfnWorks 輸出結果與 PCE 模型預測結果計算誤差並獲得較高的決定係數（coefficient of determination）值，故本研究初步以 PCE 為主。研究成果顯示每個裂隙參數的總敏感度指標皆大於一階敏感度之標，這意味著單一參數對於粒子的平均走時影響十分小，而參數之間交互作用影響程度較大。觀察一階敏感度指標則發現裂隙強度對平均走時影響最為明顯，這是由於裂隙強度直接影響裂隙在 DFN 中的數量，其對裂隙連通性的影響最為直接。

Meshless Node Generation for Three-Dimensional Groundwater Modeling

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Abstract

In real-time subsurface flow modeling, meshless methods have recently gained attention for their adaptability in adjusting node positions based on supplementary data. However, the pivotal aspect of computational node generation has received relatively limited discussion. This study introduces an adaptive three-dimensional meshless node placement approach, employing advancing front node generation techniques. The proposed method integrates moving window search and control points algorithms, ensuring efficiency and adaptability to specific positions of interest. Leveraging the Generalized Finite Difference, our study assesses the quality of the generated meshless nodes. Validation of model solutions against analytical solutions reveals errors on the order of 10^{-12}. Through the application scenario of an irregularly shaped aquifer, our three-dimensional node placement technique exhibits remarkable efficiency by generating up to 10,000 nodes in less than 10 seconds. The validation and application cases collectively emphasize the versatility and accuracy of the proposed method, establishing its potential for real-world hydrogeological applications.

Keywords: numerical modeling, meshless method, node generation

Ground Subsidence and Hydrological Properties in Yangon, Myanmar

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Abstract

Yangon is the former capital city of Myanmar, hosting ~2.75 % of the total population (55 millions of people) in the country. The city is bounded by the Yangon River to the south and the Bago River to the east, with the Shwegondaing-Mingalardon anticline sandwiched in between. In the past century, the city of Yangon has gradually expanded from its core area above the anticlinal crest to the adjacent low-lying flood plain. Owing to the rapid population and economic growth in the past decade, the public water supply system failed to cover the whole metropolitan, leaving a large proportion of residents dependent on groundwater from private wells. The lack of proper groundwater regulations and the increased extraction of groundwater from the low-lying flood plain raise the risk of land subsidence and flood hazards in Yangon. This study aims to derive the long-term ground deformation of Yangon by using multi-temporal interferometric synthetic aperture radar (MTInSAR) techniques. We obtain displacement time series from the L-band ALOS data for the period of 2007-2009 and from the C-band Sentinel-1 data for the period of 2015 to 2022. Our result indicates higher subsidence rates (up to 2.8 cm/yr) in the eastern flood plain area of Yangon during 2007-2009, which further increased to more than 10 cm/yr during the period of 2015-2022. In the western flood plain area, the subsidence rate is a few millimeters per year during 2015-2022. For the downtown area, the ground subsidence rate is less prominent due to the Pleistocene formations exposed along the anticline. The subsidence record obtained in the western part of the city agrees with the long-term trend of the only groundwater head record in this area. Together with the aquifer system constructed from hydrological wells, we estimate the first geodesy-based hydrogeological properties for the Yangon area.

濁水溪沖積扇補注潛勢評估與地下地質架構分析成果

林燕初[1]、賴慈華[1]、黃智昭[1]、邵屏華[1]、張良正[2]、陳祐誠[2]

為推動地下水保育與地層下陷防治，確保我國地下水資源永續利用，經濟部爰研提「地下水保育管理暨地層下陷防治第 3 期計畫」，規劃持續推動地下水補注等策略，以減緩地層下陷、精進地下水合理利用。其中經濟部地質調查及礦業管理中心參與計畫工作，規劃於濁水溪沖積扇仍有明顯下陷之區域補充水文地質調查，進行淺層地質架構分析及評估高補注潛勢區位。

110 年至 112 年度計畫已在濁水溪沖積扇，進行地下水天然補注區分級檢討及人工補注區位評估。天然補注區分級檢討部分，首先運用暫態電磁法(TEM)、地電阻(ERI)及大地電磁(AMT)方法，調查評估淺層水文地質結構，配合蒐集既有區域地電阻資料，進行空間資料同化與整合，建立三維地電阻模型。接著透過貝氏最大熵法整合岩芯資料、三維地電阻模型、岩性機率場等資訊，推估三維水文地質架構，並計算地表 30 公尺內低透水層累積厚度之空間分布，作為天然補注區分級依據。將厚度分為 6 級，而人工補注區評估則以低透水層較薄之 1、2 級分布為基礎，搭配土地、水源等資訊，於濁水溪沖積扇提出 20 處人工補注潛勢建議區位。

後續為評估人工區位補注效益，本計畫利用 MODFLOW 建置濁水溪沖積扇地下水數值模式，針對 20 處區位進行補注效益評估，推估各區位於 5 至 9 月進行蓄水補注後，鄰近地下水位抬升量及抬升範圍，並根據模擬結果，以涵養地下水資源及減緩地層下陷為目標，排序雲林扇頂、雲林扇央及彰化扇頂之區位優先開發建議。

關鍵詞：
Keyword : Recharge, Artificial Recharge, Hydrogeological Structure

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Influence of Subducting Sediment Properties and Fluid Pressure on Seismic Activity along the Subduction Zone Interface

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Abstract

Seismicity in different subduction zones exhibits significant variation in the spatial, temporal, and size distribution of earthquakes. The frequency and locations of earthquakes are commonly considered to be influenced by the thermal structure and fluid pressure at the plate interface. The properties of subducting sediments at the interface may also play a critical role, through the effects of grain size and shear zone thickness on viscous strain rates that control locking in the interseismic period. In this study, we explore how temperature, deformation of subducting sediments, and fluid pressure control the space-time distribution of earthquakes.

To achieve this, we utilize MEFISTO—a 2D spring-slider forward earthquake simulator that incorporates fault healing and couples to a fluid flow model. We apply a new composite flow law that combines pressure solution and dislocation creep flow laws. By integrating the new flow law with estimates of subducting sediment properties, we obtain the spatial extent of megathrust seismicity and seismic cycle phenomena. We also incorporate a shear heating effect in the thermal structure, which predicts locking depths consistent with seismic observations and geodetic modeling.

These updates improve our constraints on the extent of the seismogenic zone, allowing us to explore how different fluid production regimes affect the seismic cycle and Gutenberg-Richter b-values. The results provide realistic predictions of seismicity at the subduction interface and demonstrate the interplay among subducting sediment properties, thermal structure, and fluid pressure in subduction zones, offering insights into the slip behavior of subducting sediments from a microscopic view.

Keywords: megathrust fault, pressure solution, pore fluid pressure, shear heating, cementation, Gutenberg-Richter b-value

Measuring ground deformation across the Chegualin fault and Chishan fault, Southwestern Taiwan using aerial image correlation and DSM time series

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Abstract

Ground-based geodetic observations in southern Taiwan reveal a striking deformation pattern, with two sub-parallel southeast-dipping thrusts, the Chegualin fault and the Chishan fault, exhibiting opposite slip sense. A geodetic network (GNSS, levelling and traverse) installed along the freeway No.3 crossing both thrusts documented limited net shortening (15 mm/yr) occurs across both faults, but 50 mm/yr shortening across the Chegualin fault and 32 mm/yr extension across the Chishan fault. Uplift in-between the two faults increases eastward from 20 to 80 mm/yr relative to the eastern bloc. Sharp deformation gradients indicate aseismic slip on both structures.

This study proposes further monitoring using aerial image correlation and DSM time series from 2008 to 2015 to complement existing observations. The results show significant shortening (53 mm/yr) across the Chegualin fault, extending about 1 km along the fault strike. Our results also reveal rotational displacement within the central bloc with a clockwise rotation north of the freeway and a counter-clockwise rotation south of it. Challenges in quantifying extension across the Chishan fault due to vegetation remain.

Geological evidence for the reverse Chegualin fault and a steep SE-dipping normal fault near the Chishan fault has been locally found in the field. These investigations present a good consistency with geodetic observations. Ongoing surveys aim to link deformation patterns with geological structures. Eventually, this research will contribute to understanding the mechanism leading to the observed deformation and its relation to regional tectonics.

嘉義地區長期地殼變形之探討

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摘　要

嘉義地區近期頻繁的地震事件引起了當地居民的關注，使得此地區的長期地殼變形成為一個更迫切需要被關切的議題。首先在2023年8月中起一個月內，嘉義縣新港鄉陸陸續續發生9起規模3以上的地震，其中在9月5日發生了規模5.5的全台有感地震，引起極大關注，嘉義地區震度甚至達到5弱。接著在2024年2月29日，嘉義縣太保市也發生了一起規模4.9的地震。這些相對頻繁的有感地震讓嘉義居民感到憂心，是否會再次發生類似1906年規模7.1的梅山地震或是1999年10月22日規模6.4的嘉義地震等規模相當的災害型地震。嘉義地區存在著一系列的活動構造，包括九芎坑斷層、觸口斷層、梅山斷層、小梅背斜等，除了這些已知的構造，過去一年地震發生的位置與斷層機制解，更指示可能有未知的盲斷層存在。這些活動構造的存在表明該區域的應力正在持續累積，隨時有可能引發地震事件。若能深入了解這些斷層之間的相互關係和影響，將對預估未來地震發生機率和強度提供更為關鍵的資訊。長期的地殼變形觀測將有助於釐清構造應力在時間上的變化，嘉義地區累積的大地測量資料中，水準資料可追朔自2003年，還有臨時與連續GNSS站資料，這些長達20年的大量觀測資料建立在前人辛苦的測量與維護，因為有這些重要的持續測量工作，讓我們能對嘉義地區長時間且跨構造的變化有更多的分析與瞭解。另外，自2016年起，Sentinel-1雷達衛星影像的持續拍攝，提供我們更多地表資訊參考點來進行分析。針對每三年計算其速率場，利用橫跨剖面來探討區域內不同構造的結果，可觀測在不同時間段內地表變形之特徵，進而理解構造在時間上應力累積的變化行為。有了這些時序變化，並配合完整的地震監測體系，將能夠提前預警居民並提供即時的應對措施，相信對於地區的災害防治具有極大的意義。針對嘉義地區的長期地殼變形的監測，需要整合多方面的資源和技術，從地球科學、社會科學和工程技術等多個層面進行深入研究，以期更完整的來理解地區內地震活動的機制，提高預警和應對能力，保障當地居民的安全和社會的穩定。

臺南泥岩區域現今地殼運動之時空變化

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摘要

根據震測資料的解釋，臺灣西南外海存在一系列沿著增積契構造發育並呈現線性排列之泥體構造，且與現今已知的陸域背斜構造相連。然而，這些陸域之背斜構造活動是否和泥體構造之活動有關？為了釐清泥體構造的活動型態及災害性質，本研究利用橫跨臺南台地與龍船地區的大地測量資料，探討臺南、龍崎至內門地區的地殼變形時空變化，並嘗試解析泥體構造潛在影響的區域。透過文獻回顧，本研究整合出三種可能的地質模型：（1）包含後甲里斷層、龍船斷層與龍船背衝斷層等活動斷層主導本地區之地殼變形特性；（2）泥體構造主導地殼變形，且並非所有提出之斷層皆存在；（3）活動斷層與泥體構造同時影響本區域之地殼變形特性。為了釐清這些地質模型的可靠度，本研究除了針對各地質模型羅列出對應之地質與地球物理證據，更進一步採用高空間與時間解析度的大地測量資料，釐清各模型之可靠度。本研究首先使用與解析 2003 至 2023 年間經濟部地質調查及礦業管理中心安平至龍崎精密水準測線和 GNSS 連續觀測資料，並以 GNSS 連續站作為約制點，初步獲得本區域之垂直速度場。垂直速度場解算結果顯示，相對於澎湖 S01R 白沙站，除了沿海地區 5 公里內為持續下陷，其他區域皆以抬升的型態為主。在關廟至龍船地區，近 20 年累積了將近 200 - 500 mm 的抬升量。在 2010 年規模 6.4 甲仙地震與 2016 年規模 6.6 美濃地震發生時，在龍船與內門地區附近皆產生了同震抬升的型態。跨越關廟至龍船斷層區域的同震位移量較大，分別為 5-45 mm 和 80-150 mm。前人研究已經指出，2016 年美濃地震在關廟地區以東至龍船地區造成的同震位移量同時受到斷層活動與泥體構造之影響。由於甲仙地震與美濃地震之同震變形型態相當類似，也與震間速度型態相當類似，因此本研究指出 2010 年甲仙地震的發生也同樣誘發本研究區域泥體構造之活動。雖然在結合兩個地震之同震變形型態後，本研究更傾向活動斷層與泥體構造會同時影響本區域之地殼變形特性，但是本研究仍將進一步整合 GNSS 移動站與 InSAR 資料，期能提供更細緻與定量化的地質模型可靠度分析。

關鍵詞：精密水準測量、GNSS 連續站、InSAR、泥貫入體、龍船斷層。

Structural and lithological control on anomalous high strain rate in fold-and-thrust belt in Southwestern Taiwan

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Abstract

The interseismic deformation pattern in the fold-and-thrust belt of Southwestern Taiwan exhibits an extremely high and localized strain rate. Several models have been proposed to explain the geodetic observations in SW Taiwan; however, complicated structures and realistic conditions there were unconsidered in the previously proposed models and made it challenging to comprehensively understand the role of each factor and potential mechanisms. In this study, we incorporate the observations from SAR Interferometry and simulations by finite element method (FEM), considering local geological conditions, to probe the mechanisms responsible for the deformation patterns in SW Taiwan. We first process the time series of InSAR and then benchmarked with GNSS observations. The InSAR result shows a localized deformation zone along the Lungchuang fault (LCF) with an anomalously high vertical slip rate. The highly uplifted region is not aligned with the present topography, suggests that the uplift might be transient or the deformation pattern varies temporally. Subsequently, we next employ the DynEarthSol program to simulate the observed deformation pattern. Initial configuration of the model is constructed according to regional tectonic structures, various lithological properties, and fluid pressure conditions. We assess the deformation pattern caused by mud diarism, mud-cored anticline, duplex, ramp, back thrust, high-angle thrust, and specific material properties. The results indicate that the current deformation pattern in SW Taiwan is dominated by duplex at depth and the high-angle west-dipping fault west of the LCF. Additionally, elevated fluid pressure within the mudstone layer (Gutingkeng Formation), supported by bore-hole measurements, formulates a weak and prone-to-creep fault zone, facilitating aseismic and triggered slip events.

以井下光纖探討地震波起始波相

Investigation of Earthquake Initial Phase from Borehole Optical Fiber Array

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摘　要

地震波的起始波相被定義為 P 波抵達後振幅微弱且具有相對較小地震矩率的波相，其開始時間為 P 波抵達後，結束時間為速度波形開始急遽增長之前，可以提供震源破裂的訊息，並用來研究地震的起始行為。早在 1990 年代，前人就已使用寬頻地震儀所記錄的地震波來研究起始波相，一方認為起始波相的時長與地震規模呈正相關，另一方則認為起始波相的特徵與規模大小並無系統性的關聯。時至今日，起始波相的問題仍未達成共識。

本研究使用 MiDAS 計畫的井下光纖觀測資料，採樣率為 1000 Hz ，垂直深度每四公尺設有一個節點，如此高解析度的資料提供了更精細的資訊。研究方法是先將井下各節點的光纖資料進行交相關分析，解決時間差的問題後再疊加波形，以增強信噪比。接著將疊加後的波形進行低通濾波，只保留小於 20 Hz 的訊號，再人工判讀起始波相的區段。研究對象首先選擇 20220918 的台東池上地震序列，不過由於震央距離米崙觀測站超過 100 km，P 波的初達波很可能是 Pn 波相，會干擾對於起始波相的判斷。要釐清此問題，還需利用 CWASN 的地震波觀測資料來繪製此地震序列的走時曲線，確保在研究中所分析的對象是正確的。雖然池上地震序列有較多大規模的地震可供探討，但是為了避免受到 Pn 波相的干擾，研究對象將改選成震央位於測站附近 (<60 km) 的地震事件，除了可以避免上述之問題，還可以最小化地震波在地層中傳遞時的彈性衰減，接收到更乾淨的訊號。本研究旨在使用新的地震波觀測工具——井下光纖，重新探究起始波相，再次探討地震學中未解的重要科學問題，期望能帶來突破性的發現。

大雪山天池沉積物內矽藻與有機物分析所揭示之千年來水文環境變遷

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摘　要

大雪山天池位於海拔2600公尺之針葉林內，直至西元1911年以來才開始有大規模的林業。本研究分析台灣中部山地大雪山天池的沉積物內矽藻化石與有機物之TOC，TOC/TN比及δ13Corg(‰)的紀錄，重建近千年來水文氣候變遷與近百年人類活動對當地森林與水域生態系的影響。本研究使用的長46公分之短岩芯(DSS-TL-3)，根據Pb210與C14定年結果，顯示該岩心包含過去900年的古環境紀錄。

有機物地化分析結果顯示在900-770 cal BP(對應到中世紀暖期) TOC逐漸增加、TOC/TN有較大的波動，δ13Corg(‰)則逐漸變重，可能表示乾燥氣候。在770-40 cal BP(小冰期)TOC維持穩定同時些微增加，TOC/TN在前期770-550 cal BP時仍有波動，後期550-40 cal BP則非常穩定，δ13Corg(‰)在此時仍維持穩定但整體而言逐漸變輕。40 cal BP (西元1910年)以來TOC再次增加、TOC/TN轉為下降，δ13Corg(‰)再次變重，此時的環境變化可能與1911年起鄰近山區林場的開發，造成森林數量減少有關，最後再將以上資料與矽藻資料結合，重建當地的古環境變化。

Multi-scale Evaluation of Reservoir Sandstones Porosity: A Digital Rock Physics Perspective by Using Computed Tomography (CT)

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Abstract

Digital rock physics (DRP) techniques offer rapid and non-destructive means to acquire reliable digital images from reservoir samples, crucial for the geothermal, petroleum, and Carbon capture and storage (CCS) industries. The use of X-ray computed tomography (CT) facilitates the production of three-dimensional digital replicas of research materials, enabling the calculation of key properties, such as porosity and permeability. These properties are vital for assessing the capacity of storage reservoirs. The challenge in accurately determining these parameters lies in segmenting of voids within the porous rock materials, affected by the resolution limit and the partial volume effect. This study aims to ascertain the accuracy of porosity measurements at the whole core scale for CCS reservoir assessment, employing high-resolution CT systems to evaluate uncertainties at different resolutions. By utilizing advanced statistical methods for image segmentation, we minimize subjective judgment and assess the quality of segmentation by evaluating of CT-intensity clusters. Our findings offer insights into the impact of scanning resolution on the reliability of DRP applications in reservoir assessment, proposing guidelines for enhancing industrial application accuracy.

Integrating X-Ray Computed Tomography and X-Ray Fluorescence for Deciphering Turbidity Current Dynamics: A Preliminary Result

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Abstract

Turbidites are essential for interpreting sediment erosion, transport, and deposition processes, offering insights into hydrodynamic behavior and source provenance. These insights are instrumental in reconstructing past geological hazards. While core description and grain size analysis have widely been used to identify turbidite structures and component distributions, less attention has been paid to their internal sedimentary structures in three dimensions and the detailed chemical variations within sedimentary textures. The recent advancements in non-destructive, high-resolution X-Ray Computed Tomography (X-Ray CT) and X-Ray Fluorescence scanning (XRF) present a unique opportunity to quantitatively observe these structures and chemical characteristics in three dimensions. This novel approach was applied to turbidite samples from the Paliwan formation in the Hsiu-Ku-Luan River (HKL) section, eastern Taiwan. By comparing X-Ray CT and XRF data, we observed that the intensity of chemical elements aligns with grain size variations across the turbidite samples. For instance, the intensity of Ca and Sr increases with finer grains and decreases with coarser grains. Moreover, element ratios such as Zr/Rb, indicative of grain size in many studies, corroborate with X-Ray CT findings, where Zr predominates in coarse grains and Rb in clay. These results demonstrate the correlation between chemical element characteristics and internal structure distributions in turbidites, facilitated by X-Ray CT and XRF. This method offers a rapid, non-destructive means of comparing chemical characteristics with the three-dimensional visualization of structures and components, providing a high-resolution profile of turbidite properties. This advancement promises

to enhance our understanding of sedimentary processes and geological hazards.

Keywords: X-Ray Computed Tomography, X-Ray Fluorescence, Turbidites

Chinese Title: 利用電腦斷層掃描和 XRF 岩心掃描解讀濁流動力學之初探
Chinese keywords: 電腦斷層掃描、XRF 岩心掃描、濁流層

Enhancing Digital Rock Property Analysis through Noise Reduction on Computed Tomography Data

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Abstract

The advent of Digital Rock Physics (DRP) has marked a significant step in geoscience research, facilitating the evaluation of rock properties through advanced imaging techniques. Among these techniques, Computer Tomography (CT) imaging plays a crucial role by providing clear and quantitative 3D structural insights into rock characteristics. This enables the detailed analysis of digital images across various fields, including sedimentology, hydrogeology, petroleum exploration and production, and CO2 capture and sequestration (CCS). Despite its advantages, CT images inherently contain noise, mainly from statistical fluctuations due to X-ray quanta detection and electronic interference. Such noise can significantly impact the accuracy of digital analyses, affecting critical determinations like porosity and grain morphology.

Our research addresses these challenges by evaluating and applying several noise reduction techniques, including deep learning, Gaussian denoising, and Deep Image Prior (DIP). These methods have been effective in enhancing the quality of CT images, facilitating a more accurate and detailed examination of rock properties. For instance, in sedimentology, improved analysis of the SH-2b sample has enabled a more precise visualization of individual sedimentary grains, aiding in the calculation of their orientation for hydrodynamic insights. Similarly, enhanced porosity analysis through noise reduction has led to more accurate assessments of reservoir potential, shedding new light on CCS-related studies. Overall, this approach underscores the critical role of DRP in advancing core data analysis, offering a vital method for studying rock properties across a broad spectrum of geoscience applications.

Keywords: Digital Rock Physics (DRP), X-ray computed tomography, noise reduction

以介型蟲重建晚更新世屏東大鵬灣古水文變遷

蔡名憲[1]、汪良奇[1]、游能悌[2]、顏君毅[3]
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摘要

介形蟲生物層相與水深及泥質含量有關，因此介形蟲可能會受到水深改變造成的沉積物變化影響，透過群聚分析我們可以重建此地過去的水深變化及沉積物質的變化紀錄。穩定碳同位素（$\delta^{13}C$）被用作古水文學指標，用來反映過去氣候的變化；C/N 比代表有機物質的來源，用以重建附近植被的變化。透過統整多重指標可以重建出過去的環境變化及氣候變遷。

本研究的目的是透過分析大鵬灣沉積物中的介形蟲微化石以及同位素分析結果，推論過去大鵬灣潟湖的演變過程以及極端氣候事件的紀錄。在該地點取得的岩心長約 240 公尺，透過介形蟲分析計數與同位素分析結果對比，重建該地海岸線、水深變化及極端事件紀錄，預測未來全球暖化造成海平面上升及海岸線變化的關係。

透過初期定年及地化分析結果，與花粉紀錄進行比對，將 3.8 萬年的紀錄分為四個時期，分別為晚更新世(3.8~1.65萬年)主要為陸地與溼地環境，冰消期(1.6~1.1 萬年)為近海陸棚，中全新世(1.1~0.5 萬年)為紅樹林生態環境，晚全新世(0.5 萬年至今)為潟湖及河流系統。

臺灣南部全新世晚期的植被和氣候變化

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摘要

沉積物中的花粉分析可重建該地區的自然植群分佈演替歷史，進而推論出過去的氣候變化，或是記錄人類活動是否對該地區產生影響。穩定同位素分析可透過分析沉積物中的δ13C 可表示為 C3 與 C4 植物比例的變化指標，用來反映過去的氣候狀態；TOC 變化可代表輸入的有機物質保存狀態改變； C/N 比可表示為有機物的來源的變化，這反映了過去該地區的自然植群組成變化。

本研究分析位於屏東姑仔崙山中低海拔(1468.8m)濕地長 200 公分的沉積物內花粉組成結合穩定同位素資料以重建出台灣南部山區的古氣候變遷以及古天災事件。在這項研究中，較高的 C/N 比值和相對較低的 δ13C 表明，研究區域的逕流條件較好，C3 植物的比例較高，這表明公元 350 至 900 年為溫暖期，屬於前中世紀溫暖期（Pre-MMWP）。此外，在公元 900-1300 年期間，C/N 值略有上升，δ13C 值也有所上升，這表明該地區的逕流條件較好，C4 植物的比例略有增加。這一時期可歸因於中世紀暖期（MWP）。然而，在公元 1300-1800 年期間，C/N 比值略有下降，δ13C 沒有出現任何明顯變化。這可能表明該地區的逕流條件較低，表明氣候條件較乾燥，可歸因於小冰河時期（LIA）。

山崩機制與運動模型:降雨與地震觸發因子

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摘　要

在臺灣，順向坡滑動以及土石流為常見的災害，對居民的生命財產造成巨大威脅。而本次研究區域為台北陽明交通大學校區內，位於棋哩岸山南側、臺北盆地北側邊緣之丘陵地上，地勢南高北低，平均坡度在20%以上。地質主要為第三紀中新世木山層與第四紀松山層，其中木山層以厚層砂岩偶夾薄層頁岩與薄層砂、頁岩互層為主，松山層主要由未固結泥砂組成，地層傾角在19°S~25°S之間，因地層的傾向和坡向大致相同而為順向坡。

若是山坡的坡腳支撐消失，再加上達到某一程度的降雨量或是地震強度，則該山坡地上的坡體就會沿著地下的滑動面向下滑動。因此本研究透過現地調查以及文獻蒐集，了解邊坡破壞的實際情況以及地質特性，利用GeoStudio軟體來建構陽明交通大學棋哩岸山坡地的數值模型，再使用這套軟體中的SEEP/W模組和SIGMA/W模組來探討在颱風或其他降雨事件帶來的雨水滲流影響下，邊坡從降雨、入滲、孔隙水壓上升、地下水位變化、材料遇水弱化，以致坡體崩塌變形之關鍵因素及影響。

藉由GeoStudio數值模擬軟體，以真實坡體狀態進行模擬，由SEEP/W模組的穩態滲流分析設定年平均雨量作為暫態分析前之坡體含水量狀態，再以暫態滲流分析，選用2015年蘇迪勒颱風8/6-8/9在竹子湖站的時雨量進行分析，此目的是為了分析模型內孔隙水壓隨時間之變化，以及地下水之流速變化，再利用SIGMA/W的應力-耦合分析模式進行分析，計算降雨滲流之孔隙水壓變化以及各時階下坡體的應力應變狀態。本研究將釐清在甚麼樣的降雨條件下會使頁岩遇水弱化，使陽明交通大學之順向坡坡體發生位移甚至破壞，以及了解土體及岩層在降雨後的應力應變情況，未來可提供防災、邊坡 安全分析上之參考。

應用多元遙測技術在地質災害監測與評估

Application of Multi-Source Remote sensing Techniques in Geohazards Monitoring and Assessment

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摘 要

隨著台灣經濟的快速發展，基礎交通設施的興建日益增加，但受到近年自然氣候變遷之極端事件影響，加上台灣地形變化大、山區陡峭且地質構造複雜之特性，使得鄰近地質敏感區、土石流好發區及邊坡崩塌熱區之交通設施結構穩定性受損，進而衝擊交通安全及民生經濟。

以臺灣鐵路為例，每當颱風事件或雨季連日降雨所帶來之豐沛降水量亦或是斷層錯動所引發之地震事件，均易影響鐵路交通運行及其設施運營，如連日降雨引發的集集水里二號隧道崩塌事件、台鐵瑞芳猴硐路段坍方及台東地震導致多處鐵路橋樑錯位、軌道變形扭曲等，均突顯鐵路交通工程建設初期選址、規劃及後續環境評估等工作，掌握區域地質構造、活動性評估與環境監測的重要性。

本研究針對台鐵山里隧道北口路段，該路段於 2023 年受小犬颱風事件侵害，由颱風所帶來之大量降水量夾帶上游土砂形成土石流，覆蓋鐵路軌道，進而影響台東線之鐵路運行。本研究將結合多元多尺度遙測技術，以搭載 L 波段之雷達衛星配合多時序合成孔徑雷達干涉(Multi-Temporal InSAR, MT-InSAR)，迅速掌握研究區域之廣域地表變形活動熱區，並搭配無人機光達(UAV Light Detection and Ranging, UAV-LiDAR)產製高精度數值高程模型(Digital Elevation Model, DEM)，以地形計測測繪技術，由廣域尺度至工務邊坡尺度，進行細部監測，以靜態地形判釋結合動態地表變形，評估研究區域易致災環境因子，並提供後續鐵路工程修繕規劃意見。

誌謝 本研究計畫承蒙 台灣世曦工程顧問股份有限公司「臺灣鐵路管理局邊坡巡檢精進系統建置」計畫案提供研究經費 謹致謝忱。

中文關鍵字:多時序合成孔徑雷達干涉技術、高精度數值高程模型、工程地質災害

Keyword：Multi-Temporal InSAR, Digital Elevation Model, Engineering Geohazards

動態降雨山崩潛勢模式建置

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摘　要

動態山崩潛勢模式係透過探討山崩時空變遷，來釐清前期事件對於後期事件誘發山崩之關聯性，據以提供複合事件誘發山崩之熱區預測，進而橋接地震與降雨兩種山崩潛勢模式，並結合即時地震、即時降雨資料，來建置地震-降雨關聯性動態山崩潛勢模式。為了歸納地震對於降雨誘發山崩的影響，前期以集集地震影響最為嚴重的中部地區為研究區，挑選地震後不同時間點之颱風事件，包含桃芝颱風(2001)、敏督利颱風(2004)、辛樂克颱風(2008)及莫拉克颱風(2009)，配合6 m數值地形建置降雨誘發山崩潛勢模式。本研究基於集集地震建置地震誘發山崩潛勢模式成果，接續建置降雨誘發山崩潛勢模式，以利後續兩種山崩潛勢模式橋接。

傳統山崩潛感分析是以多年期山崩目錄為訓練資料，以多變量分析或其他方法建立山崩潛感模型。近年來以事件誘發山崩目錄為訓練資料，在潛感因子中加入促崩因子建立模型成為主流，稱之為事件型山崩潛感模型。但事件型山崩潛感模型深受建模事件影響，而有與促崩因子(降雨或地震)分布相依的情形。為了減少促崩因子相依對於山崩預測的影響，本研究改以多年期山崩目錄建置山崩潛感，稱之為事件獨立型山崩潛感，亦稱為基礎山崩潛感，可代表該區域之地形、地質體質條件概況，解釋該區域的長年崩塌趨勢。基礎潛感值與山崩崩壞比呈現正相關的趨勢(以韋伯分布方式上升)，在相同的降雨條件下，基礎潛感值越高其崩壞比也越高，也就是地質地形條件脆弱地區容易發生更大量的山崩。本研究以基礎山崩潛感分析其與各事件之山崩崩壞比、雨量因子間的關係，擬合崩壞比曲面，即為該雨量因子之降雨誘發山崩潛勢模式，並據以繪製山崩崩壞比圖。各分區結果顯示基礎潛感圖預測訓練事件之正確率即可達70~80%，部分分區接近90%，山崩崩壞比圖預測驗證事件之正確率亦可達70%左右。由於數值地形解析度提升，比對過去研究成果可發現許多相對更為危險的區域被標示出來，如丘陵區及向源侵蝕的崩塌，或是過往的危險區域有精準的區位，如溪溝型的崩塌。除靜態山崩潛勢比對，採用山崩崩壞比擬合曲面可用來推估該研究區在颱風或降雨期間的山崩動態變化，即不同的降雨強度下的岩屑崩滑山崩崩壞比分布，以及可能發生崩塌的區位及面積，提供防災規劃參考。

震後多時序降雨事件之山崩預測模式

Landslides prediction model for post-earthquake multi-sequence rainfall events

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摘要

為了達成山崩即時性預測及山崩動態變遷模擬之目的，須考慮到不同類型誘發山崩事件相互影響且隨時間推移變化之山崩預測模式。此模式中應包含不同促因之山崩預測模式也就是地震誘發山崩模式及降雨誘發山崩模式，另外則是地震後降雨或降雨後地震等複合式事件影響的山崩預測對策。本研究為建立震後多時序降雨事件之山崩預測模式，先於廣域以及 44 處小研究區，進行集集地震後多年期降雨事件之山崩分析，以觀察地震對於後續降雨誘發山崩的影響。

本研究統計大甲溪、烏溪及濁水溪流域由集集地震所誘發之山崩，於 2000 年至 2016 年間在各流域內仍佔有之山崩面積比例，以初步了解集集地震誘發山崩隨時間之變化。由廣域研究發現，集集地震誘發山崩所佔面積比例大約在震後 5 至 6 年左右降至較為固定的狀態，陡峭的大甲溪溪谷則需較長時間。所謂較為固定的狀態，也就是指部分地震誘發山崩植生復育，而部分山崩裸露則較長期的留在坡面上。

一次強震事件在空間上有不同地震強度的分布，並不是每個地方受到地震的影響都一樣，對後續降雨誘發山崩的影響也不一樣。為進一步釐清各種地質地形分區受到不同地震強度之後續山崩變化，本研究考量不同受震強度、岩性、地形坡度、颱風降雨量等條件，挑選位於集集主震最大地動加速度 250gal 以上區域內之 44 處研究區，以集集地震前/後之降雨事件序列，進行各種降雨因子(最大降雨強度、最大 3 小時累積雨量、最大 24 小時累積雨量及總雨量等)與事件誘發山崩崩壞比之統計分析，以率定地震強度對於不同地形地質分區及降雨條件下的後續山崩影響及其影響時間。

由 44 處小研究區之地震前/後多時序降雨事件山崩目錄統計分析，綜整出下列現象：(1)強震後造成之坡面岩體強度降低或林間不穩定崩積物，於震後 1 年內易受較小降雨沖刷而崩出，崩塌區位較偏向山脊。(2)地震與降雨誘發山崩於坡面之好發區位不同，地震誘發山崩偏向山脊，降雨誘發山崩偏向山溝或溪谷兩側，地震對易受降雨引發山崩的地形區域影響時間

有限。因此，強震發生 1 年之後，降雨量與誘發山崩崩壞比關係大多可回復至地震前之關係。(3)強震後 2-5 年間，位於愛氏震度 2 m/sec 以上受創較重地區，由地震所誘發之較大規模山崩其後續易受降雨持續刷深或擴大；位於愛氏震度 2 m/sec 以下地區，地震誘發山崩多呈植生復育的狀況。(4)強震約 5-6 年後，地震山崩裸露面上的崩積物可能沖刷至較少，使山崩範圍較為固定。

將上述分析成果應用於震後多時序之降雨山崩預測時，首先，本研究採用之山崩預測模式包括地震與降雨兩種誘發山崩模式，模式核心為基礎潛感值-震度(或降雨強度)-崩壞比之擬合曲面經驗式，基礎潛感值為無地震或降雨時之地形地質條件易崩趨勢，經驗式代入預測或即時的愛氏震度(降雨強度)，即得到崩壞比空間分布，可用來進行山崩潛勢分級或進一步推估誘發山崩面積及區位。

其次，地震後隨時間推移之降雨誘發山崩潛勢推估對策為：(1)由於地震與降雨誘發山崩於坡面之好發區位不同，兩者應採不同之山崩預測模型。(2)地震後 1 年內降雨之山崩潛勢推估，各地點可採地震與降雨兩種預測模型所推估之潛勢等級高者，如此可兼顧坡面上既存之地震誘發山崩、後續沖刷出之山崩及降雨誘發山崩。(3)強震後 2-5 年間降雨事件之山崩潛勢，位於愛氏震度 2 m/sec 以上地區可採地震與降雨兩種預測模型所推估之潛勢等級高者；位於愛氏震度 2 m/sec 以下地區，可僅採用降雨誘發山崩潛勢結果。(4)強震 5 年後降雨事件之山崩潛勢預測，各地點均僅採用降雨誘發山崩潛勢結果。

本研究山崩預測模式可得到每個網格(6m*6m)之崩壞比值，透過計算各斜坡單元內平均崩壞比，再乘以斜坡單元面積，可推得各斜坡單元可能之崩塌面積，將此面積分配於斜坡單元內之最高崩壞比區位，即為預測之山崩區位。由於地震後續幾年間，坡面上會同時存在地震誘發且未植生復育之山崩及降雨誘發山崩，建議預測山崩區位之處理方式如下:(1)強震後 1 年內預測山崩區位，可用地震模型預測之山崩區位加上降雨模型預測之山崩區位。(2)強震 1 年後，因地震所誘發之山崩受各地地形條件及降雨情形不同影響，植生復育或沖刷擴大等後續狀況較難以預測，因此建議採用降雨模型預測之誘發山崩區位加上前一年之山崩目錄，即可很好的預測強震後續降雨事件後之山崩分布情形。

關鍵詞： 多時序降雨事件、降雨誘發山崩、山崩預測模式

以機器學習方法建立考量歷史崩塌及空間關聯性的崩塌潛勢評估模型

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摘　要

台灣地處板塊交界帶，受造山運動及季風氣候影響，形成高強度侵蝕環境，且隨著氣候變遷造成的極端氣候日益增加，崩塌的發生將更加頻繁。因此，事前預警及防減災對坡地安全十分重要。隨著地理資訊系統（GIS）和大數據的發展，使探討地文、水文、及人文等多種因子對坡地穩定的影響成為可能。其中，透過機器學習建置崩塌潛勢評估模型是目前最受矚目的方式之一。

傳統使用機器學習方法的研究，多以易取得的地形、地質、及水文等資料為模型訓練特徵，但在崩塌頻發的台灣，已發生崩塌地區的穩定性及植被覆蓋相對較差，易再次發生崩塌。因此，本研究以歷史崩塌事件作為模型訓練特徵之一，並探討其重要性。另外，由於崩塌事件範圍不定、規模不一，將研究區域切分為網格分析易使網格相關性消失，破壞崩塌場址的連續性，進而影響模型評估準確性。因此，本研究引入自然語言轉譯領域的自注意力機制，自動化全局考量序列中各單元相關性，以解決網格間獨立性的問題。期許能夠建立廣範圍、高精度的崩塌潛勢評估模型。

結果顯示，加入歷史崩塌事件特徵能大幅提升模型評估能力，不論是否考慮空間相關性，都有明顯提升。而自注意力方法使模型在precision及recall中取得較好平衡並降低資料偏誤造成之缺陷，更適用於實際防減災操作。本研究建立的評估模型亦將在地質差異大的區域以及不同年份進行測試，確保其在空間及時間上具有良好的泛用性，期能取得與過往的研究相比，更穩定及良好之崩塌潛勢評估表現。

Evaluation of Macroseismic Intensity, Ground Motion Pattern and Earthquake Sequence of the 2022 Mw 5.9 Keng Tung Earthquake in Eastern Myanmar

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Abstract

On 21 July 2022, a moderate Mw 5.9 earthquake occurred approximately 30 km southeast of Keng Tung (Kyaing Tone) Township in Shan state of Eastern Myanmar. Despite this region being previously identified as a relatively low earthquake hazard region compared to the central and western Myanmar, the Keng Tung earthquake caused building damages and landslides near the epicenter of the mainshock and was felt across a large area of the mainland Southeast Asia, extending from the southern Yunnan to the central Thailand. To understand the macroseismic intensity of this event, we collected felt reports and damaging photos from social media and internet news, to evaluate its ground motion intensity based on the EMS-98 scale. We also used instrumental data collected from the Myanmar National Seismic Network, the Thai Seismic Monitoring Network, and the Vietnam Seismic Network to relocate the Kengtung earthquake sequence, and to determine the mainshock's focal mechanism. For the mainshock event, our macroseismic investigation shows that areas southwest of epicenter were affected by stronger intensity than other areas, suggesting the mainshock rupture may propagate southwestward unilaterally. Such interpretation agrees well with the mainshock's focal mechanism result, as well as the aftershock distribution on the ruptured fault. Our interpreted intensity also roughly aligns with the intensity predicted by Atkinson et al., 2014 for West North America, and the intensity predicted Atkinson and Wald, 2018 for California, suggesting the mainland Southeast Asia may have similar crustal antennation behavior to the region of West North America. We also test different GMPEs and GMICEs to look for appropriate empirical ground motion equations that can be applied to this area. All of these results will contribute to establishing a better model to describe the earthquake damage for central part of mainland Southeast Asia.

活動構造三維數值模型於情境地震模擬應用

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摘 要

為了解地震事件與地下構造之間的三維空間關係，國家災害防救科技中心於2015 年起與國立臺灣大學及國立成功大學合作，建置臺灣地區三維地質構造數值模型(3D Geological Structure Model，GSM)，該模型以三角網格面描述斷層面樣貌。在地震發生後，透過自行開發之模組可以快速篩選地震事件與其最鄰近的活動斷層面，並且以視覺化方式說明地震事件與活動斷層面之三維空間關係，輔助地震應變使用。此外，為評估災害性地震可能造成的災損，可以藉由數值方法模擬情境地震於特定區域之地動值。本研究將應用 GSM 估算最大地震規模、建立有限斷層面及震源破裂模型，並計算各三角網格之參數，如面積、走向、傾角、破裂時間等資訊，結合數值地形模型、淺層速度構造、三維地下速度構造、莫荷面等數值模型，計算三維地動值，地動模擬之結果後續可以提供災害評估、損壞評估及防救災演練等應用。

關鍵字：三維地質構造數值模型、情境地震模擬、震源破裂模型

Keyword：3D Geological Structure Model, ground motion simulation, source rupture model

地質封存整合注儲與井洩漏不確定性之風險模擬案例研究

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摘　要

地質封存場址風險評估為維護封存場安全的重要工作，其中儲集層地質參數的不確定性往對注儲時的儲集層的壓力分佈有重要影響，也連帶影響了後續洩漏風險的可能性。本研究延續前期成果，使用美國能源部風險聯盟(National Risk Assessment Partnership, NRAP) 的最新整合型風險評估模式工具NRAP-Open-IAM，以台西盆地的臺灣候選場址為案例，建立包含儲集層地質參數不確定性與井洩漏不確定性之整合風險評估的案例研究。案例建立流程包括，輸入所需之案例場址資料收集、儲集層重要地質參數之敏感度分析、洩漏井模擬與風險模擬，與最後輸出之井洩漏風險評估分析。案例場址為已有公開資料之彰濱場域，以TOUGH建立儲集層模式，進行每年一百萬噸二氧化碳之單井大規模注入模擬，將儲集層參數敏感度分析之結果轉換為NRAP-Open-IAM的儲集層輸入檔；然後使用NRAP-Open-IAM進行場址儲集層注儲不確定性下的不同井洩漏情境的井洩漏風險模擬。

分析結果顯示地層參數對於壓力反應影響甚巨，尤其滲透率的對儲集層升壓有明顯作用，明顯影響後續井洩漏模擬結果。依據本研究整合注儲與井洩漏不確定性的洩漏風險評估的結果，在最樂觀的情形下甚至無法引起二氧化碳洩漏至地表；然而在最悲觀的情形下，注入井體處就有超過操作壓力與井體受到破壞造成洩漏的可能。二氧化碳最大洩漏率發生在注入井關閉時。儘管如此，單井悲觀情境洩漏的總量仍遠小於總注入量的1%，顯示只要能及時處理因應，案例的井洩漏仍為可控制的風險。因此建議於注入時進行即時壓力監測與操作管理，以因應因地質異質性的可能帶來的不預期升壓，降低洩漏風險。

地形資訊於深度學習山崩廣域判釋之成效

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摘　要

為減少人為的干預與專家知識的人力付出，可藉由深度學習模型利用多層神經網路架構，萃取出目標物之抽象特徵來達成。衛星影像進行山崩判釋的領域中，過往許多研究輔以不同資料最佳化判釋結果，有使用前、後期影像基於變遷的概念偵測山崩的可能區域，亦有基於單期RGB影像，另外增加其他地表輻射資訊如：衛星影像NIR波段、NDVI、NDWI，或地形資訊如：DSM、slope、aspect作為深度學習模型的輸入層偵測山崩，又或者，先以高解析度的RGB影像與DEM進行特徵圖的融合，再進入到模型做山崩偵測。綜合上述，除了影像本身資訊外，過往研究亦使用地形與植生等能代表崩塌地位於「坡地」與「裸露」特徵的因子，做為模型主要的訓練資料。然而，在廣域判釋的情形中，臺灣山崩形態多樣，除了陡峭邊坡的淺層崩塌，亦有包含部分山溝的土石流型崩塌，和橫跨陡峭至和緩地形的大規模崩塌，上述崩塌其對應的地形範圍，並非單純坡度陡峭之地區。因此，地形特徵與影像崩塌特徵未能直接相關，且地形資料與衛星影像在特徵的意義上差距大，若直接將地形資訊與影像作為模型輸入層之輸入，未必能得到較好的判釋效果。本研究嘗試使用屬於CNN系列的deeplab v3+模型，探討廣域分析中地形資訊於山崩判釋效果，以SPOT-6影像之不同波段組合，搭配地形做測試。結果顯示，在假色融合影像與坡度圖做為輸入層之組合結果最佳，山區建物、道路以及河道在加入坡度資訊後誤判大量減少，然而，部分河道旁的山崩仍有河道判釋為山崩的一部分的情形，仍有待更進一步地調整改善空間。

台灣西南長支距海域震測資料全波形逆推初探

Preliminary full waveform inversion test on long-offset marine seismic data in offshore SW Taiwan

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摘　要

本研究嘗試以 MGL0905-10 測線進行全波形逆推初期測試，此測線以東橫跨了高屏陸坡的下部及上部斜坡，選取該線測試的位置遠離泥貫入體，以減少如衰減效應對於相位偏移造成的影響。資料利用 CGG 公司開發之震測資料處理軟體 Geovation 2，進行震測資料輸入、幾何定位、濾波、振幅修正、去幽靈反射等步驟，最後再施以不同的低通濾波，以決定最佳的逆推起始頻率。

將上述資料進行速度分析所得之時間域疊加速度模型，轉成層間速度模型，並轉至深度域，編輯後得到初始深度域速度模型。該模型與上述震測資料再輸入至 SEISCOPE Consortium 團隊開發之 TOY2DAC 軟體，以全波形逆推方法更新速度模型。

在一開始模擬波形時，為了尋找合適的震源，本研究測試三組不同方法產生震源漣波：第一組，來自最小平方法估計的震源漣波、第二組，移除鬼波後的海床疊加震源漣波以及第三組，將第二組漣波再移除氣泡效應的震源漣波，以比較模擬炸點聚排與真實資料間的差異，並判斷是否存在週波跳失的問題。

關鍵字：台灣西南海域、震測資料處理、全波形逆推

SW Taiwan Offshore、Seismic Data Processing、Full Waveform Inversion

臺灣東南海域臺東海槽北緣之構造特徵與機制：利用海岸山脈最南端地層與構造進行海陸域對比

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摘　要

由於歐亞大陸邊緣與呂宋島弧之間的斜向聚合，使得臺灣成為最適合研究隱沒系統轉變為碰撞系統的天然實驗室之一。而臺灣東南區域，陸域的海岸山脈以及近岸海域的臺東海槽，被認為是了解初始弧陸碰撞的重要過渡帶。為了瞭解臺東海槽最北端和海岸山脈最南端之間的構造發育，我們進行了陸域野外調查以及海域多頻道反射震測，透過資料探討海陸域地體架構的連接關係，進一步瞭解區域演化歷史。

陸域研究部分，我們將焦點放在海岸山脈最南端的永豐斷層，以及位於永豐斷層西南側、與永豐斷層走向接近平行的利吉斷層。在縱谷內部，永豐斷層為利吉層與八里灣層的邊界，走向近南北向，為向東傾的逆斷層，然而在海岸山脈最南端，永豐斷層的位置與走向尚未定論，接觸關係也存在不同的解釋，如平移斷層接觸(Chen, 2022)、逆衝斷層接觸(Huang et al., 2018)或沉積接觸(Lai et al., 2021)，根據野外調查，我們認為永豐斷層走向約為東西向，並且更傾向將其解釋為是一個平移構造的接觸關係。利吉斷層同樣為走向近南北向的逆斷層，並且在海岸山脈最南端同樣有向東南方轉彎的趨勢。

海域研究部分，本研究震測資料範圍主要涵蓋緊鄰陸域的臺東海槽。地層部分，利用震測地層學的方法，我們將剖面中不同的震測相進行區分，並且與陸域海岸山脈的都鑾山層、蕃薯寮與八里灣層、卑南山礫岩、利吉層等地層進行對比與連接。構造部分，根據水深與震測資料，顯示臺東海槽最北端存在數個呈現東西走向的崖狀地形，從形貌上來看，似乎呈現一系列右移的特徵，震測剖面亦有斷層的特徵。我們認為這些崖狀地形可能是源起海岸山脈最南端的構造，與陸域永豐斷層、利吉斷層的向海延伸活動有關。我們嘗試納入新期構造的角度探討臺東海槽最北端的構造特徵，透過區域的地震分布與震源機制解，可以看到臺東海槽最北端有許多走向滑移分量的地震存在，其中以右移分量的震源機制解居多，更加支持了崖狀地形可能為一系列右移斷層的解釋。我們認為這些東西向右移斷層的存在，可能代表呂宋島弧和中央山脈之間的板塊邊界進行南北向的走向滑移運動時，內部為了調適地殼變形與破裂量而發展出的東西向轉移斷層系統，顯示臺東海槽最北端和海岸山脈最南端受到弧前盆地逐漸閉合的影響，因此反映了初始碰撞的構造轉變過程。

東沙陸緣高原之構造特徵與地質演化：利用多頻道反射震測資料

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摘　要

陸緣高原係指於大陸棚與下部陸坡間、突出而平坦之地形特徵。他們的成因或與大陸分離的薄化地殼碎片，以及富岩漿陸緣破裂過程中因熱點等之岩漿作用而形成的火成體等有關。陸緣高原在大西洋、印度洋等區域的大陸邊緣皆有發現，但在邊緣海則較少相關討論。在南中國海(South China Sea, SCS)的北部陸緣，我們在東沙環礁周邊辨識出了一個陸緣高原(後續以東沙陸緣高原稱呼，Dongsha marginal plateau)。為了了解東沙陸緣高原的構造性質以及地層層序-地體構造發展歷史，本研究使用多頻道反射震測(multi-channel reflection seismic, MCS)並且整合過去發表之文獻，進行不整合面構造等時圖之繪製。

透過與過去發表文獻之剖面進行關聯，我們在反射震測剖面中辨識了數個層序邊界，包含Tg (基盤頂部反射面，~65 Ma)、T7 (張裂不整合面，~32 Ma)、T6 (~23 Ma)、T5 (~20 Ma)、T4 (~16 Ma)、T3 (~10 Ma)以及T2 (~5 Ma)。從Tg、T7的分布，我們在東沙陸緣高原下方辨識出了一個基盤高區、基盤高區西北的狹長盆地、以及西南的區域性凹陷，可與前人文獻之東沙隆起、珠一凹陷、以及白雲凹陷對比。高區朝東北-西南方延伸並且可能受古背斜影響，上方還缺乏古近紀地層(同張裂地層)。基盤高區的西邊邊界為北北西-南南東走向、海床落差約300公尺的東沙斷崖。此外，透過T2不整合面的分布，我們辨識出了一個抬升事件(東沙運動)。本研究提出：白堊紀期間，古太平洋板塊向北隱沒形成古島弧，造成東沙陸緣高原第一階段隆起運動，而古島弧成為岩石圈異質帶，抑制了後續南海北部陸緣的張裂作用。在南海張裂時期，除了張裂斷層(rifting fault)平行古隆起構造軸發育，張裂盆地間以轉換斷層(transfer fault)連結彼此之斷層系統，並於斷層間形成規模較侷限的拉張盆地。東沙陸緣高原隨後再經歷了第二期抬升事件(東沙運動)，推測為馬尼拉海溝隱沒作用造成的岩石圈彎曲。在東沙運動期間，東沙斷崖不僅限縮岩石圈彎曲造成的抬升範圍，同時也抑制沿再活化斷層噴發之岩漿活動向西擴散，因此斷崖東、西兩側抬升運動具明顯的強度差異。

台灣東北部外海斷層特徵及斷距分析初探

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摘　要

台灣北部經歷了晚新生代的造山運動而現處於造山後期的垮山階段。台灣東北陸域大部分斷層雖仍以逆斷層為主，然而作為垮塌造山帶向北部外海的延伸，海域之地質架構主要由區域性伸張所形成的一系列東北—西南向的正斷層系統為主，因此近岸海域或可視為逆斷層與正斷層構造交替轉換之處。為了解近岸構造的構造轉換之特徵，我們利用了台灣東北外海新收集的多頻道反射震測資料，再加上重新處理的剖面資料和已發表的剖面資料，來重新檢視了解這些斷層詳細的幾何形態，討論海域正斷層和陸域逆斷層在地質解釋上的關聯性以及海域斷層延伸性，並希望能進一步討論可能的活動性。

在本研究的震測資料中，可以看到由幾個正斷層和斷塊所組成的一系列半地塹盆地，我們在其中辨認出兩個震測層序不整合面，分別代表斷塊頂部和填充的沉積物頂部。透過震測層序不整合面的分析和解釋，可以得知每條正斷層斷距的分布情形。其中觀察到，這些正斷層的斷層錯距朝近岸逐漸減小，直到陸域斷層性質轉為逆斷層；朝向離岸的方向，我們發現這些斷層的斷距也逐漸減少並消失。此外，兩個震測層序不整合面的深度分布變化不一致，這可能暗示著這些斷塊的形成和斷層的活動並不是按照一定的順序所進行的。故本研究希望針對斷層錯距進行量化與分析，進而分析斷層活動的開始和累積的斷距，並以此探討斷層之發育。這將使我們能重新探討海陸斷層構造之間的關聯，並進一步了解這些斷層在台灣造山帶垮塌期間的發展。

臺灣東北海域斷層構造分布與震測特徵

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摘要

臺灣北部經歷了造山與後造山垮塌作用，同時也受南沖繩海槽張裂活動影響，在東北海域，沈積地層及構造特徵也紀錄了早期擠壓及現今拉張應力作用影響，也發育了數條海域斷層。為了解臺灣東北海域的地體構造與斷層系統，透過近期新海研 1 號所收集的新地球物理資料，搭配過去海研一號及海研二號歷年航次所收集的多頻道反射震測資料，並輔以底質剖面資料與多音束水深資料進行分析，再透過進階的震測成像與水深資料處理技術，在臺灣東北外海重新辨識了外金山、野柳、小野柳、八斗子及鼻頭角等五條主要的海域斷層。此五條斷層在淺部皆呈現東北-西南走向之東南傾正斷層，其中外金山斷層長度約 30 公里，於剖面上具有切穿至海床的特徵，並可以對應至海床上分段的外金山線形，向陸域端可對應至山腳斷層。野柳斷層於近岸區域切穿至海床，長度約 13 公里，並對應至近岸的野柳線形，外海方向為盲斷層特徵，長度約 14 公里，總長約 27 公里。小野柳斷層位於野柳斷層東側斷塊半地塹盆地內，其皆未切穿至海床，長度約 14 公里，往外海方向可能發育為多組分段排列的小斷層而難以追跡。八斗子斷層於近岸區域切穿至海床，長度約 11 公里，在外海方向呈盲斷層特徵，長約 17 公里，總長度約 28 公里。鼻頭角斷層於近海切穿至海床，並可以對應至陸域端的基隆斷層，其向外海方向則轉為盲斷層，長度約 10 公里。研究結果顯示，分布於臺灣東北海域的一系列正斷層系統，部分具有切穿至海床的特徵，且於近岸淺水區域也有觀察到與斷層分布趨勢吻合的海床線形特徵，可能指示為斷層錯動而導致的斷層崖地形，並且向陸域端方向也與臺灣北部陸上的斷層分布相符，推測臺灣東北海域之斷層應與陸域斷層有所關連。本研究透過不同尺度之地球物理資料的綜合解釋，更新臺灣東北海域的斷層構造分布，並界定出五條主要的斷層構造，對於未來之地質風險評估工作，也能提供進一步的資訊。

關鍵字：臺灣東北海域、多頻道反射震測、海床線形特徵、斷層構造

利用聯合反演折射與反射震測資料探討南海北部大陸邊緣地殼速度構造

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摘　要

南海北部被認為是南海最早期開始擴張的位置，其大陸邊緣也記錄了早期張裂的歷史，因此南海北部大陸邊緣為研究大陸地殼張裂、破裂到海底擴張的理想地點。在此區域的下部地殼，常發現有一顯著的P波速度異常高速(>7km/s)特徵，稱為高速帶(High-velocity layer)，這種高速帶常被解釋為在張裂時期岩漿活動添附到下部地殼所造成的底侵作用(Underplating)有關。因此對高速帶的研究能夠更深入了解岩漿活動的程度及其與裂谷時期歷史的關係。雖然南海北部大陸邊緣已有許多高速帶的研究，然而對於高速帶在南海的空間分佈與厚度變化仍有歧見。在本研究中，我們利用一條在南海北部大陸邊緣地殼速度構造剖面的重處理解釋，檢視過往研究歧異之處，並結合已發表文獻中不同剖面上高速帶的特徵，編繪南海北部大陸邊緣高速帶的空間分佈，冀以增進我們對南海北部大陸邊緣高速帶性質的了解，並更進一步增加我們對南海早期裂谷期發展的認識。我們首先透過分析多頻道反射震測資料所求得的基盤形貌與淺層速度，以此獲得基盤以上沈積地層的速度構造，作為求地殼構造的初始速度模型。隨後我們將初始模型與海底地震儀所收集到的走時資訊結合，利用TOMO2D軟體來進行反射與折射走時資訊的聯合逆推，完整建構一個在南海北部大邊緣的地殼速度模型剖面，提供莫荷面深度與高速帶分佈的可靠資訊。在最終速度構造模型中，我們觀察到地殼厚度向大陸側漸厚，而在這地殼漸厚的過渡帶之下部地殼發現有厚數公里的高速帶特徵，透過確立高速帶的分佈與性質，除了對過往歧異的成果提出有效的佐證，我們將再更進一步討論南海北部大陸邊緣在張裂期與破裂時之構造演化與岩漿活動的相互關係。

變遷中的海洋岩心庫，邁向跨域整合之路：發展現況與新進展

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摘　要

對於臺灣這類海島型國家來說，透過『建置一站式海洋沉積物採樣技術與岩心分析量能』策略，落實臺灣周遭關鍵海域探勘、二氧化碳地質封存、礦產資源調查之目標是有其必要性。據此，高品質長岩心紀錄（>20公尺）與多面向岩心分析成為解密地質紀錄的重要關鍵。這不僅提供海域地質基礎資料與過去海洋環境變遷，以探討地質災害事件型 vs自然環境條件型之發生頻率與機制外，同時，呼應並落實政府「2050年淨零排放」策略，支援黑潮海洋能與自主探勘能源等能源轉型所需之海域地質探勘、自然碳匯之大洋藍碳等的能力建構。

國研院海洋中心十多年淬鍊累積，打造國內首座完備『海洋岩心實驗室』，且為唯一首座連續取得ISO 9001國際品質認證。其具備高品質的岩心基本／非破壞性分析儀器、舒適的作業空間外，恆溫4度與-20度低溫冷凍儲存環境之岩心冰溫庫，系統性管理臺灣鄰近海域的珍貴沉積物樣本。同時，發展成熟之多項岩心非破壞性分析技術，提供海／陸域地質紀錄之快速、經濟成本且具高解析度的量測，更精進勵進研究船海洋岩心採樣量能，樣本回收率維持80%以上。並與國際接軌，參與數個重要國際聯合探測航次，貢獻於能源轉型與海洋科學研究上，這包括R/V *JOIDES Resolution*之IODP 368航次、R/V *Marion Dufresne*之台法EAGER航次和R/V *SONNE*之台德 SO-266海床岩心淺鑽航次。

於既有基礎上，建置一站式海洋沉積物採樣技術與岩心分析量能。中長程策略規劃以最大化海洋沉積物採樣之深度與廣度，臺灣周遭關鍵海域分年分區執行，並適時導入先進技術，掌握前瞻技術適時引進，另一方面，擴大海洋岩心分析量能，優先擴充地質紀錄基礎分析設施。再者，為實現區域融合和均衡發展，海洋中心與東華大學攜手合作。透過設施共享、建置岩心倉儲跨網絡合作、深化一站式海陸域地質紀錄分析以及岩心設施平台經驗交流，逐漸形成跨海／陸域學術研究廊帶。透過區域性聯合倉儲、關鍵設施之跨領域資源共享，期能有效節省國家資源、優化實驗室品質管理與技術，為邁向跨域整合之目標而努力，並成為海洋科學研究的堅強後盾。

臺灣海域熱液礦產資源地質地物資料庫

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摘　要

經濟部中央地質調查所(現為地質調查及礦業管理中心)自 2016 年起推動臺灣東北海域礦產資源潛能調查工作，由臺大、中央、中山等多個工作團隊針對臺灣海域進行資源潛能調查研究，調查項目涵蓋反射震測、地熱流、地熱模擬、高解析聲納、磁力、地球化學、海床觀測等各式調查工作。為能有效地管理及應用各項調查資料，國立臺灣大學海洋研究所協助地礦中心進行各類資料彙整與建立資料庫之工作，並進行資料展示與維護作業。過去 8 年間已在周遭海域執行了 40個調查航次，收集了 4,814 公里的反射震測剖面、5,030 公里的海床底質剖面、49站地熱流量測、約 3,825 平方公里的多音束水深資料、1,382 公里的高解析底拖聲納剖面、24 站海底地震儀及 7,141 公里的磁力資料;在地球化學資料收集方面，彙整了 57 站採樣資料與 32 站海水層柱資料，針對樣本分析工作，則包含岩心描述、地化特性、礦物組成、磁學性質及間隙水地化資訊等多種資料。在海床觀測方面，收集了約 169 公里的海床觀測影像測線資料及 1,921 張特殊海床觀測照片，另外也完成了 3 個 ROV 調查航次的資料收集工作，保存了大量海床觀測影像及水下遙控無人載具調查觀測影片、地溫紀錄與採樣成果。在資料庫的建置過程中，亦將資料的格式加以標準化並增加屬性資料，不僅能完整保存原始資料，亦利資料的使用與交換，本資料庫針對所收集資料，利用地理資訊系統，將各項資料進行數位展示，依據資料屬性分類、需求導向、工作年度及主題目錄建立各式資料圖層，再將大數據空間資訊進行視覺化工作，以展示綜合分析成果，並發展相關加值服務。另針對多元的地化量化分析資料，則透過 MySQL 關聯式資料庫的建置進行管理，使地化資料成果能完整地展示。透過本工作的累積，希冀未來能讓這些珍貴的調查資料能永續使用，發揮更高的效益與價值。

關鍵字：熱液礦產資源、海洋資料庫、地理資訊系統

南海中洋脊海底擴張晚期之火成活動

Magmatic activities near mid-ocean ridge of SCS at the end of seafloor spreading

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摘　要

南海海底擴張時期約在37.8-16.7 Ma，於前人研究中得知南海海底擴張歷經許多擴張方向改變，且海底擴張停止前之擴張速率突然增加 (約17.6-16.7 Ma) 。我們利用海洋中心長支距多頻道震測 (Long-offset Multi-Channel Seismic)設備，於2019年之LGD1901航次所蒐集跨越南海中洋脊之LGD1901-02震測資料，透過幾何定位、帶通濾波與垂直速度分析等處理，以得到較清晰的震測影像剖面，藉以瞭解南海中洋脊之火成活動。其中，從影像中可得知南海中洋脊之南北海盆並非對稱構造，南部海盆的火成活動較北部活耀，且有火成岩體入侵抬升沉積層序之現象發生，進而觀察其抬升現象可至更新世 (Pleistocene)地層，且此期間仍有活動斷層產生。然而，北部海盆斷層與火成岩體入侵活動大部分皆發生於中新世 (Miocene)之地層中。另一方面，比對磁力資料，發現中洋脊南邊的海盆擴張速率較北邊的快，可能為南邊隱沒板塊的拉力影響，導致海底擴張速度也隨之增快。綜合上述結果，推測在南海中洋脊海底擴張晚期，受到南海南邊之隱沒板塊重量增加導致隱沒速度加快影響，整體海底擴張速率突然增加 (約17.6-16.7 Ma)。接著，南海海底擴張於中新世 (Miocene)中期停止，北部海盆的火成活動也隨後於中新世 (Miocene)晚期停止。但是南部海盆可能仍受到隱沒帶影響，仍於更新世 (Pleistocene)地層發現些許斷層，岩漿活動也在持續至更新世 (Pleistocene)地層。

關鍵字:火成岩體、中洋脊、海底擴張、南海
Keyword: Igneous rock, Mid-ocean ridge, Seafloor spreading, South China Sea

Physical properties from non-destructive analysis as tracers for source-to-sink dispersal of modern marine sediments offshore eastern Taiwan and implication for related geological events

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Abstract

Little is known about the past extreme events and likely characteristics around Taiwan that were caused by earthquakes, typhoons, and climate forcing. A detailed paleoclimate reconstruction from offshore eastern Taiwan will enhance our understanding of natural climate variability in the low-latitude Pacific and its teleconnections with changes at high latitudes across glacial and interglacial periods via East Asian monsoon and Kuroshio Current. However, the reconstruction of a continuous, high-resolution paleoceanographic changes and related geological extreme events from offshore eastern Taiwan since the Last Glacial Maximum is limited due to the scarcity of comparable marine records. In this study, the marine sedimentary records we investigate is box cores and piston/gravity cores retrieved along the southern offshore east coast of Taiwan, which is a location of modern winter pathway of the Kuroshio Current, with highly dynamic interactions of the East Asian monsoon, Kuroshio Current, and riverine input from Beinan River. Here we conduct non-destructive measurements on marine sedimentary core representing characteristics of typical sediments and sedimentary structures in deposits of offshore eastern Taiwan by analyzing multi-sensor core logger (MSCL). In addition, we further establish and validate chronology of those marine cores by using C-14 dating and high-resolution non-destructive data (e.g., color reflectance data and physical data from MSCL). Different from traditional technique of stable oxygen isotope stratigraphy, this novel stratigraphy will provide another candidate for other marine cores below the present carbonate compensation depth. Furthermore, we apply relationship between MSCL data-gamma density and magnetic susceptibility in the East China Seas could be an indicator of local coastal rivers and surface currents. This approach will be applied to those box cores and further test its applicability on source-to-sink or Kuroshio Current index.

枋寮海底峽谷上游之淺部沉積層構造

Shallow sedimentary structure at the upper Fangliao canyon

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摘　要

位於臺灣西南海域之枋寮峽谷，峽谷上游並未有陸上河川連接，卻能夠往下切約400公尺的深度，且周圍遍佈泥貫入體的構造，其峽谷形成原因可能為泥貫入體抬升，導致滑移崩塌與底流的運輸，逐漸形成枋寮峽谷，且峽谷下游也受到泥貫入體影響分支為二後進入深海平原區。我們利用2023年11月之勵進研究船T56測試航次，於枋寮峽谷上游進行多音束聲納 (Multi-Beam Sonar)與底質剖面儀(Sub-Bottom Profiler)等設備進行地形地貌與淺部沉積層資料蒐集。接著，從底質剖面影像中發現，位於枋寮峽谷上游西北側，有由東向西滑移崩塌的區域，對比前人研究的泥貫入體分布位置，推測為泥貫入體抬升影響，導致此方向的崩塌。此外，在峽谷東側之淺部沉積層影像亦觀察到氣體通道。不僅如此，枋寮峽谷兩側亦受到泥貫入體抬升影響，逐漸往峽谷方向滑移崩塌，所以可觀察到峽谷底部並不平整，有些許的崩塌物。最後，我們認為枋寮峽谷上游發育受到兩側泥貫入體分布位置影響，且從底質剖面影像中得知現今泥貫入體仍在活動抬升導致邊坡滑移崩塌，且若底流機制持續存在，將崩塌物運輸至深海平原，枋寮峽谷上游未來會逐漸變寬。

關鍵字: 枋寮海底峽谷、泥貫入體、滑移、底質剖面儀
Keyword: Fangliao canyon, Mud diapir, Slide, Sub-Bottom Profiler

臺灣海峽離岸風力發電潛力場址區地質風險評估

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摘　要

為實現綠色經濟發展目標，臺灣積極投入離岸風力發電開發工作。在過去幾年中，學界在業界與經濟部地質調查及礦業管理中心的委託下，已在離岸風力發電潛力場址區域進行了海洋地質與地球物理調查，同時進行地質災害潛勢評估。臺灣因受弧陸碰撞影響，有活躍的地震活動，且因常受到颱風以及暴雨侵襲，導致島上發生強烈的侵蝕作用，使大量沉積物快速傳輸至周邊海域。而臺灣海峽在離岸風力發電開發過程中，因地質構造與火成活動，或因海洋環境與快速沉積作用，也發現多種地質情況可能對海域風場開發與運維造成災害風險，甚至導致風力發電機之基礎與電纜損壞。本研究透過分析於臺灣海峽收集來的多重尺度地球物理資料，包括多頻道反射震測剖面、海床底質剖面和多音束水深資料，對於臺灣海峽離岸風電潛力場址區域之地質災害風險特徵進行了解。藉由震測地層學分析與震測剖面上辨識出來的前陸基底不整合面以及末次冰期不整合面，掌握此區地質構造活動年代，並辨識四類潛在的地質災害風險，包含：（1）流體活動，（2）斷層構造，（3）沙波遷移，以及（4）堅硬地層。臺灣海峽有許多斷層分布，但多數被深埋，對於風力發電機的影響不大，然而切穿過末次冰期不整合面的淺層斷層，其影響則至關重要。此外，臺灣海峽也已辨識出許多流體活動特徵，本研究認為過去發生的溜樁事故可能與富含流體的淺部地層發生液化有關。沙波主要分布在彰化外海及澎湖群島周圍，其波高約為3至10公尺。強烈的底流導致沙波快速移動，可能增加風力發電機基樁和電纜淘刷風險。臺灣海峽中部有較淺的堅硬地層分布，如玄武岩層，在選擇場址時需避開。本研究顯示海洋地球物理與地質調查有助降低離岸風力發電開發過程中的地質災害風險。

臺灣地震活動度展示系統

邱昊德、梁文宗、李文蕙、李其芳、羅仲宏

為了提供學界唾手可得的地震活動資訊並推廣臺灣的地震科學教育，我們建立了一套地震活動的展示系統，其中包括原始數據、靜態展示、動態展示和角色扮演的互動操作網頁遊戲。

原始的地震目錄數據是由「中央氣象署臺灣地震與地球物理資料管理系統(GDMS)」提供，是歷年來氣象署地震中心藉由氣象署地震觀測網(CWASN)所偵測到的地震事件彙編而成。除此之外，GDMS 網站也典藏 CWASN 和強地動觀測網(TSMIP)的地震波形資料，其他尚有 GNSS、地下水位及地磁場等地球物理資料可供使用。GDMS 系統並具有查詢和下載等功能，且輸出的結果呈現方式主要包括測站資訊表格及地圖、互動式地震波形圖、專業格式資料檔等，方便用戶快速獲取所需資訊。靜態展示的部分位在「臺灣地震資料研究中心(TECDC) 」的地震活動地圖功能裡面，用戶可以查詢近 90 天內氣象署的地震速報資訊或 GDMS 的歷史典藏資料，使用者可依時間、空間、深度及規模查詢然後直接呈現在地圖上，適合特定地震序列的快速瀏覽。動態展示則是 TECDC 的提供的臺灣地震活動度動畫，這個動畫目前呈現了從 1990 年開始的規模大於 4 地震目錄資料，類似一個小型播放器，用戶可以調整播放進度、速度、音效等設定以增加了互動性，適合學校或博物館的長期展示。最後，互動操作部分為 TECDC 教育推廣功能的網頁遊戲「勇闖震源城」，玩家化身為保衛地球的勇士，通過角色扮演的遊戲來學習地震定位的方式，以及應對地震時的避難知識。我們希望這套系統能讓更多人了解臺灣的地震活動，並鼓勵對地震研究有興趣的學生投入臺灣的地震科學研究行列。相關連結請參考：

GDMS：https://gdms.cwa.gov.tw/

TECDC：https://tecdc.earth.sinica.edu.tw/

2024 年 M_W 7.5 日本能登半島地震破裂過程的能量分配
Energy Partitioning During the 2024 M_W 7.5 Noto Peninsula (Japan) Earthquake

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摘要

本研究利用時間域解迴旋分析 2024 年 M_W 7.5 日本能登半島地震的震源時間函數，再依此得到此地震的上揚時間(rise time)、地震矩(seismic moment)、震源輻射能量(radiated seismic energy)、靜應力降(static stress drop)及動應力降(dynamic stress drop)。之後，再依照實驗室岩石破裂實驗的動應力降－正向應力及動摩擦應力－正向應力的經驗關係推估能登半島地震的動摩擦應力，最後在滑移減弱模型下(slip-weakening model)，建構 2024 年能登半島地震在破裂過程的能量分配。結果顯示此地震的地震矩 2.1×10^{20} Nm、震源輻射能量 2.31×10^{15} Nm、破裂歷時 46 秒、上揚時間 8.53 秒、靜應力降 2.04 MPa、動應力降 1.78 MPa 及動摩擦應力 13.19 MPa。依動摩擦應力得到破裂過程的破裂能(fracture energy)與摩擦熱(frictional heat)總合為 1.0×10^{17} Nm，此也相當於地震過程的變形能(strain energy)，亦即在斷層面上的做功(work)，此時的地震效益(seismic efficiency)約0.0226。依此想法，本研究也估算 1999 年集集地震的變形能為 3.27×10^{17} Nm，此也相似 Wang (2004, GRL) 由滑移模型所估算的變形能 3.208×10^{17} Nm。

關鍵詞：2024 年能登半島地震、上揚時間、震源輻射能量、動摩擦應力、變形能、地震效益

Keywords: 2024 Noto Peninsula earthquake, rise time, radiated seismic energy, dynamic stress drop, strain energy, seismic efficiency

車瓜林斷層情境地震動模擬分析

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摘　要

車瓜林斷層由高雄市內門區向南延伸至橋頭區，總長約25公里，由一個主斷層以及多個分支斷層組成斷層帶，寬度約30-130公尺，於2022年被劃為第一類活動斷層。斷層沿線有許多重大基礎建設，如橋頭科學園區、國道一號、國道三號、高鐵等，橋頭科學園區做為半導體、電動車產業聚集重鎮，若斷層破裂引致地震動可能對鄰近產業群落產生影響，故本研究選定車瓜林斷層進行地震波模擬分析，了解斷層鄰近區域受地震動影響的程度。

本研究使用三維有限差分法進行低頻地震波模擬，納入地表地形、三維速度構造模型作為本研究模擬計算之模型建置基礎資料，此外，本研究亦利用斷層鄰近實際中小規模地震與測站接收到之觀測波形進行比對，驗證模擬成果可信度。而後，針對車瓜林斷層設定特徵震源情境，考量特定規模、破裂尺度、震源機制、破裂速度、破裂方向性等震源參數，並在斷層面上設置地栓作為能量釋放主要位置，進行地震動情境模擬。透過情境模擬分析PGV、PGA、震度等地震動參數在空間中分佈，了解車瓜林斷層破裂引致地震動對鄰近區域造成之影響。

台灣即時地震科學資訊系統(Taiwan Earthquakes Scientific Information System)2024年版

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摘要

本系統目的在於建置台灣地區地震的即時資訊彙整平台，以氣象署的地震速報為基礎，整合學界的科學成果（地球物理及地質等即時資訊）與其他基本圖資。內容涵括氣象署的地震速報結果、發震時間、震源位置與規模，以及各地震度等。 一旦發生大區域有感地震，系統收到氣象署的速報即觸發學界之震源反演的計算，近即時提供數個運用不同資料、方法與震波速度模型的震源解，並且提供BATS寬頻測站之即時地震波形線上展示；同時也利用P-Alert強震網所記錄的全台即時PGA繪製shakemap；本系統也彙整該地震前一週及後三週的地震活動作為地震序列活動之參考。 另外可疊加的背景圖層包括歷史地震活動、震間變形、由地礦中心的WMS服務所提供活動斷層、地質圖等。希望本系統對孕震構造的快速辨識、 餘震的評估，以及其他可能觸發之地質災害的判定等，能有所貢獻。本平台以Django作爲後端資料管理，然後以Vue前端框架加上Leaflet地圖平台作為使用者介面，適合在電腦、手機或平板等裝置上直接操作，歡迎各界踴躍使用。TESIS的網址為https://tesis.earth.sinica.edu.tw

關鍵字：台灣、即時地震科學資訊、Django、Vue、Leaflet

Probabilistic seismic hazard assessment for Taiwan: TEM PSHA2025

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Abstract

The Taiwan Earthquake Model, in developing the new generation seismic hazard assessment, termed as "TEM PSHA2025", adjusted seismic source parameters to reflect the latest data. To evaluate seismic hazards from seismogenic structures around Taiwan, the surrounding area was divided into 30 zones. Seven earthquake catalogs from 1900 to 2022 were merged to calculate background seismicity in each zone, excluding foreshocks and aftershocks. Compared to the previous version (TEM PSHA2020), the new model incorporates newly identify onshore structures, offshore seismogenic structures, and modify onshore structures. Additionally, new pairs of multiple structures rupture, identified by Coulomb stress triggering and topographical evidence, and newly identified historical events from two fault in a time-dependent seismic model. Furthermore, the seismicity in the Ryukyu and Manila subduction zones were reevaluated based on updated parameters, such as slip rates and interface geometries.

Finally, by utilizing the aforementioned parameters combined with a database of the average shear-wave velocity in the top 30 meters at each site and considering uncertainties caused by different strong ground motion prediction equations, we have developed a seismic hazard map. Compared to the TEM PSHA2020, this version of the seismic hazard map shows a lower hazard in central Taiwan, partly because of reduced seismicity in recent years and a lower earthquake probability on the Chelungpu Fault that just ruptured in 1999. Conversely, other areas exhibit a higher hazard, a phenomenon resulting from the proximity of some seismogenic structures offshore near Taiwan, and higher slip rates of certain onshore structures. The results of this study will contribute to subsequent research on seismic risk assessments and the promotion of disaster prevention strategies in the public sector (such as earthquake scenarios, disaster evacuation and rescue drills, etc.).

An annual report of Real-Time Moment Tensor Monitoring System

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Abstract

Real-Time Moment Tensor Monitoring System (RMT, https://rmt.earth.sinica.edu.tw/) is a real-time seismic monitoring system designed to automatically detect seismic activity in Taiwan. The system can provide information such as the original time, source location, moment magnitude, and source mechanism within two minutes after an earthquake event. The monitoring area ranges from 119.2°E to 123.0°E, 21.0°N to 26.0°N and depth of 2 kilometers to 180 kilometers. The grid spacing is less than 0.05 degrees in the horizontal direction and about 2 kilometers in the vertical direction, varying with depth. The system combines centroid moment tensor (CMT) inversion technology, grid search methods, 3D Green's functions calculated using the spectral element method, and real-time broadband seismic record. The early RMT system operating from 2012 to 2015 with 1D Green's function, which has been upgraded to 3D Green's function version since 2015. This report compares the results of seismic events detected by the RMT in 2023 to early 2024 with the results of the seismic events detected by Central Weather Administration (CWA) and the centroid-moment tensor solution (CMT) of the Broadband Array in Taiwan for Seismology (BATS). The average differences in event time and epicenter location were approximately 1.05 seconds and 4.8 kilometers, respectively. Most source parameters are close to the BATS CMT solution. The long-term goal of the RMT system is to provide real-time source information for medium and large earthquakes for rapid seismic risk assessment.

Keywords: real-time monitoring, moment tensor inversion, source parameters, 3-D Green’s function, computational seismology

以近場地震資料分析 2021 年台灣壽豐地震序列 $2 \leq M_L < 4$ 的震源歷時：隱喻震源非自相似性

Investigating Source Duration of the 2021 Shoufeng (Taiwan) Earthquake Sequence with $2 \leq M_L < 4$ using Near-Field Seismograms: Implications for source non-self-similarity

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摘要

本研究利用在 2021 年花蓮壽豐地震序列方圓 50 公里內由 BATS 所記錄的近場地震資料調查此地震序列 $2 \leq M_L < 4$ 的震源歷時(T)與地震矩(M_0)的關係。先前研究指出 2021 年壽豐地震序列 $M_L < 4.0$ 地震的 E_S/M_0 和 M_0 近乎正比(E_S：地震能量)(Hwang et al., 2022, TAO)。以理論而言，當 T 為定值，表示與 M_0 無關，則 $E_S/M_0 \propto M_0$，但這仍缺乏觀測上的佐證。因此本研究以頻率—波數積分法計算合成 P 波，並與觀測 P 波比對以求得壽豐地震序列的震源歷時。結果顯示 T 與 M_0 呈現弱相關，可將 T 視為與 M_0 無關，因此，本研究從觀測上印證了 $E_S/M_0 \propto M_0$ 的關係。除此之外，由於 2021 年壽豐地震序列 $2 \leq M_L < 4$ 的震源歷時趨於定值，並不符合震源自相似性的特徵。

關鍵詞：震源歷時、地震能量、地震矩、震源自相似性

Key Words: Source duration, Radiated seismic energy, Seismic moment, Source self-similarity

Seismic Velocity Contrast Analysis Along the Longitudinal Valley Fault System, Taiwan, Utilizing Fault Zone Head Waves and Direct P Arrivals

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Abstract

Fault zone head waves (FZHWs) offer insights into fault structures at seismogenic depths. We investigate the northern segment of the Longitudinal Valley (LV) fault system, a major suture zone between the Eurasian Plate and the Philippine Sea Plate. The analysis focuses on 22 stations within a 60 km by 28 km area along the fault, using ~8000 small-to-moderate earthquake seismograms recorded from 2012 to 2018. Employing Ross and Ben-Zion's algorithms, we detect 272 robust head waves from 149 events, primarily along the west-dipping Central Range fault, indicating a consistent velocity contrast across this segment. Validation of automatic FZHW picks confirms accuracy through particle motion, polarization, and moveout analyses despite complexities in subsurface structures and topographical changes. Our investigation reveals a constant moveout pattern from P wave to FZHW time differences, indicating a shallow bimaterial interface significantly impacting the wavefield near or beneath stations. We fit the moveout and constant arrivals with two models to the differential P and head wave arrival times to explore possible local variations of the constant trend. The Akaike Information Criterion applied to the constant and classical moveout pattern suggests spatially complex significant results that, together with the depth distribution of the involved events, indicate a deeper-reaching bimaterial interface. This analysis yields an average velocity contrast of approximately one per cent, aligning with previous FZHW studies along major plate boundary faults. Overall, this study enhances understanding of fault structures in the LV fault system and underscores the importance of FZHWs in providing high-resolution fault information.

Utilizing Synthetic Data for the Characterization and Detection of Fault-Zone Trapped Waves (FZTW) through Full-Waveform Simulation

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Abstract

As seismic waves propagate in proximity to fault zones, the interaction with diverse physical parameters induces the formation of trapped waves. The generation of trapped waves is associated with the physical properties of subsurface structures, including the geometry of fault zone, the contrast in wave impedance, and the influence of shallow sedimentary layers. This study employs a three-dimensional finite-difference method to simulate the propagation of seismic waves and explore the characteristics of trapped waves within fault zones to address the following issues: (1) By manipulating various physical parameters of the fault zone, we observed the emergence of trapped waves and alterations in waveforms. (2) We endeavor to apply automated techniques for identifying trapped waves and validate them using the simulated dataset.

In the first step of the study, fictitious fault-zone models were utilized to simulate trapped waves. Drawing from the previous study of Li and Vidale (1996), a three-dimensional Y-shaped fault-zone model was constructed to understand the characteristics of trapped waves under specific conditions. Moreover, we have adopted the techniques developed by Ross and Ben-Zion (2015) for identifying trapped waves within fault zones. By extracting signal characteristics from time series, the algorithm evaluated five parameters, including dominant periods, energy concentration, peak amplitude delay, and amplitude ratios, to identify the possible trapped waves in space and time from seismograms. We aspire to employ this technique for large-scale data analysis in the future, thereby expediting data processing and enhancing identification efficiency.

Extreme supershear rupture with discontinuous jumping propagation during the 2023 Türkiye M7.8 earthquake

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Abstract

Earthquake ruptures typically advance sequentially across multiple faults or uneven regions, a phenomenon referred to as cascade rupture. However, our analysis of the 2023 M7.8 Türkiye earthquake, employing finite-fault joint source inversion, revealed the occurrence of discontinuous jumping. The primary fault plane adjacent to the splay fault experienced an immediate substantial rupture, while the deeper portion of the northeastern fault plane displayed significant triggered slip before the main rupture front arrived. Through seismic centroid analysis and finite-fault inversion, we estimated that rupture speeds within these slip patches reached approximately 6.0 km/s, surpassing the local S-wave velocity, indicating an extreme supershear rupture. The dynamic triggering mechanism induced jumping rupture in these areas, resulting in an apparent rupture velocity exceeding the local shear wave velocity. These findings underscore the significance of dynamic triggering in adjacent fault systems during large earthquakes, influencing the extent and complexity of rupture propagation.

高樓層建物受震波影響之分析與模擬

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摘　要

台灣因位於環太平洋火山地震帶上，使得斷層及孕震構造運動活躍，因此對於地震災害風險性評估及其應變對策至關重要。而藉由對台灣各地區在地震事件中較易受震波影響之高樓層建物進行分析與探討，能夠幫助我們有效建立的地震災害風險評估之標準，並且透過分析之結果建立結構物安全監測(SHM)系統，使地震事件發生後得以快速精確的掌握建物之受損情形。

本研究以台南都會區中樓高12層之國立成功大學資源系系館為研究場域，以測試高樓層建物於台南台地上於地震時所受之影響。藉由於資源系館1樓與7樓裝設之P-alert與三分量速度感震器，成功紀錄微震資料與嘉義，高雄，花蓮此三方向的地震紀錄，並由地震波型的分析，掌握在地震事件發生時，其地震波對於建物產生之放大效應、震動頻率、質點運動等資訊。而在永續城鄉發展的前提下，本研究將高樓震波資訊配合結構物安全監測(SHM)之模擬，可精準測定高樓建物在地震時之影響之層間變位與殘餘變位角。以此確認高樓各樓層間震後之健康度，作為安全監測之依據。

以微地動探討山腳斷層於大屯火山群區域內的分佈與構造

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摘　要

根據經濟部地質調查及礦業管理中心對台灣北部活動斷層的研究，山腳斷層是一條位於台灣北部的第二類活動斷層，類型為正斷層。在陸地上的長度約為 34 公里，呈北北東走向，可以分成南北兩段。南段從新北市樹林區向北延伸至台北市北投區，長度約為 13 公里；北段則是從台北市北投區向北延伸至新北市金山區，長度約為 21 公里。由於山腳斷層北段為大屯山的火山岩所覆蓋，以及可能受到斷層活動的影響，區域內過去曾發生大規模地滑，大部分的斷層跡可能掩覆在大規模地滑的堆積物之下，以至於目前對於山腳斷層北段還無法研判此區域斷層的明確位置。

微地動（microtremor）主要是由自然（例如風和海浪、微地震）或人為活動所產生，由於在微地動的訊號中除了包含波源和傳遞路徑，也包含了地下的構造信息。因此，我們可以藉由微地動陣列的量測和資料分析，來了解山腳斷層北段區域的地下構造，以及進行斷層位置的推論。本研究中首先針對北段的山腳斷層進行微地動陣列的量測，我們在每個量測區域將陣列佈設的範圍涵蓋所有斷層跡的可能位置，包括在大屯山區、竹子湖以及竹子山腳至金山平原等區域。至於小觀音山至竹子山中間的區域，因為受到地形和道路的阻礙，目前無法進入此區域進行量測，未來在時間和人力允許的情況下，將以步行的方式進入此區域進行微地動陣列的量測。

根據在竹子山腳至金山平原量測所得到的頻散曲線，顯示出位於竹子山腳的陣列量測到的波速較慢，此結果符合該地區屬於較為年輕的地層，而位於金山平原的陣列則是量測到較快的波速，此結果也符合該地區屬於年代較老的地層。另外，我們在金山平原量測所得到的頻散曲線，顯示出其頻率在 0.6 Hz 時屬於低速，反應的地層深度大約在地下 800 多公尺深的位置。而此結果反映的是否為斷層的位置，在未來有更多量測數據，並進行速度構造的逆推，以及參考鄰近岩芯、震測剖面等資料之後，將會幫助我們釐清此一關鍵議題。

國道 3 號中寮隧道區域環境噪訊分析

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摘要

在均勻的散射波場下測站間的連續記錄交互干涉波形(Cross-Correlation Function, CCF)可以近似於測站間的格林函數，因此，透過被動式的地震噪訊干涉技術可以監測構造物理性質的變化。國道 3 號田寮段分別切穿旗山斷層與車瓜林斷層這兩條南部重要的活動構造，為了探討斷層活動對隧道的結構影響，本實驗室於 2020 開始於國道三號田寮段周圍架設由 33 顆便攜式地震儀所組成密集陣列，進行長達一年的環境噪訊觀測。由於本密集陣列的平均站間距小於 1 公里，干涉波形有機會可以得到高頻的格林函數，得以進行淺層構造的監測。隨著都市化的快速發展，對於近地表(<200m)地層的辨識分析與監測越來越重要，但是在人口稠密的區域不適合使用主動式震源測勘，因此利用環境噪訊層析成像這類的非破壞性、非侵入性、低成本和相對高精度的被動式測勘就非常適合，也能直接利用都市中車輛行駛所產生的訊號，然而噪訊能量分佈的若非均勻，可能會造成干涉波形與真實格林函數之間的差異，因此本研究將針對背景高頻訊號進行時空特性的分析，釐清訊號的來源，將可成為未來進一步研究的基石。透過單站的頻譜隨時間的變化，在 1-12Hz 以上的訊號有明顯的日夜變化，並且 PSD 於空間上的分佈顯示離國道較遠與位於中寮隧道上方的站強度較小的現象，因此可以推論主要應是車輛導致的，但是 CCF 所顯示的頻譜強度並沒有看出日夜變化，由於 CCF 是交互相關的結果，因此可以知道在此區域應當有一個除了車輛以外的穩定訊號來源，為了了解此訊號的頻段，會進一步細分不同頻段之強度隨時間的變化，而沒有日夜變化的頻段將是此研究所要分析的訊號，再以 grid search 的方式找出訊號的來源位置，以此訊號與各測站的距離與到時來算出此陣列下方的位於高頻的 1D 速度構造，而低頻的部份將用 Eikonal 的方式來補齊，以此兩種方法得到陣列下方的完整的 1D 速度構造。

Improving subsurface imaging in southern Taiwan from multimode Rayleigh wave dispersion analysis of ambient noise cross correlation functions: The Frequency-Bessel Transform method

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Abstract

The empirical Green's function (EGF) retrieved from cross-correlation function (CCF) of ambient seismic noise fields at two stations has been proved effective for probing subsurface structures. While derived fundamental-mode surface wave dispersion yields S-wave velocity (Vs) structures with unprecedented lateral resolution, especially in the crust, it has limited depth resolution and nonunique model problem due to its smooth and depth-decaying sensitivity kernel. To address this, we employ the Fourier-Bessel Transform (F-J) method, developed by Wang et al. (2019), for dispersion analysis of the EGFs at periods of 2-20 s, collected as part of the SALUTE project and permanent stations in southern Taiwan from 2021 to 2023. Dividing stations into four subregions: from west to east the Coastal Plain (CP), Western Foothills (WF), Central Range (CR), and Coastal Range (CoR), we apply the frequency-vector wavenumber transformation to the spectrum of the CCFs for each subregion, integrated over the entire surface to obtain the F-J spectrograms as a function of wavenumber and frequency. The derived dispersion curves reveal distinct characteristics and phase velocities across subregions. In the CP and CoR, both fundamental and first higher mode dispersion curves are evident. The derived phase velocities at ~3-10 sec, particularly in the CP, differ significantly from previous tomographic models, suggesting potential overestimation of S-wave velocities in the crust covered with thick sedimentary layers. Conversely, no higher-mode Rayleigh waves are detected in the metamorphic massifs of the CR, and the fundamental-mode phase velocities agree with the model predications. Our preliminary results demonstrate the efficacy of the F-J method for extracting multimode surface wave dispersion and potentially improving subsurface imaging capabilities in geologically complex regions like southern Taiwan.

Phasenet 模型再訓練對小地震監測能力的影響分析

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摘　要

地震波形辨識在地震監測系統中扮演著關鍵角色，尤其對於小地震的監測，受到環境中的雜訊影響，難以準確判斷地震 P 波與 S 波，使得系統對小地震的偵測能力下降，且定位結果存在一定的誤差。為解決此問題，人工智慧技術近年被引入地震訊號辨識領域，以提高辨識準確性並降低誤判率。然而，在台灣地區應用以國外資料訓練的模型仍存在誤報風險，因此有必要利用台灣地區的地震資料進行模型訓練，以提升模型在當地的適應性。本研究旨在探討對於小地震監測能力的影響。我們以 Phasenet 模型為基礎，透過再訓練的方式利用台灣地區的地震資料進行實驗。我們選擇了嘉南地區作為研究區域，並針對個別地震測站進行模型訓練，以更好地考慮地震站的獨特性和雜訊情況。透過挑選 2023 年的連續資料進行模型再訓練，我們專注於嘉南地區的地震事件，確保模型能夠適應當地的地質環境和地震特性。研究結果顯示，Phasenet 模型再訓練能夠有效提升地震監測系統的效能，特別是在小地震監測能力方面。通過比較模型再訓練前後的準確性和偵測率，我們發現再訓練後的模型在小地震監測方面表現顯著優於原始模型。此外，我們還進行了與 Seisbench 套件中的 denoise 功能相關的實驗，結果顯示這一功能有助於提升模型對小地震的偵測能力。總的來說，本研究的結果強烈支持 Phasenet 模型再訓練對於地震監測系統的效能提升，尤其是在小地震監測方面。同時，我們使用 Seisbench 套件來標準化模型與資料集的訪問，並提供各種常見的處理和資料擴充操作，進一步支持地震監測系統的改進。這一研究為地震監測系統的改進提供了有價值的參考，同時也為未來相關研究提供了新的思路和方法。

Structure of Subducting Lithosphere under Southern Taiwan Inferred from Multiple Arrivals of Intermediate-Earthquakes using SALUTE Array

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Abstract

In order to better understand the tectonic process transitioning from termination of subduction to initiation of collision, we have constructed a Southern Array for the Lithosphere and Uplift of Taiwan Experiment (SALUTE) since late 2021. During 2022-2023, there are 6 intermediate earthquakes with ML3.3-4.8 well captured by SALUTE broadband stations showing systematic variations of P waveforms from northern Luzon subduction zone through structures underneath southern Taiwan. In the preliminary study, we compare the three events almost in-line with the E-W transect of SALUTE array but various in their focal depth. Those events show consistent waveform features: (1) a large secondary arrival appears about 2-3.5 seconds after first P and the separation slightly increases with distances; (2) a small time-delay for the first arrival near eastern Central Range and another larger delay right west of Chaochou fault. In addition, small precursors are clearly detected at two consecutive stations in Central Range for the deeper event with depth exceeding 100 km, which is most likely associated with leaking energy traveling along the lower interface of the subducting crust dipping toward east. As for the feature (1), the second P arrival with amplitude comparable to initial P implies a notable interface near the source, which would require further investigation carefully using 2D waveform simulation. For the feature (2), the time delays are generally consistent with the local crustal structure, i.e. the effect of thick sedimentary basin under Kaoping.

Seismic Activities near Chaochou Fault from SALUTE Array

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Abstract

SALUTE (Southern Array for the Lithosphere and Uplift of Taiwan Experiment) is a cross-shaped array that consists of broadband stations both on land and offshore, with an E-W line transecting the entire southern Taiwan from Kaohsiung to Taitung and N-S line stations laterally distributing around Chaochou Fault. The installation of array began in October 2021 and completed with 31 stations in total by 2024 spring. With small interspacing average of about 7 km, the configuration of SALUTE array provides good coverage in southern central southern Taiwan for small earthquake detections. Chaochou fault is a left-lateral fault with minor thrust component. However, recent major earthquakes near northern Chaochou fault, such as 2010 Jaishian, 2012 Wutai and 2016 Meinong, all occurred at depths deeper than ~20 km. The shallow seismic activities near Chaochou fault are still unclear. In the preliminary analysis, we concentrate on the seismicity located in Maolin region during 2022-2023 when the data acquisition is most complete. We use both Antelope and SeisComP for initial scanning and event locations. Small events as small as ML0.5 are detected. After picking refinement, we will use HypoDD to obtain better relocated seismicity for further interpretations. The purpose is to identify possible structures that may be connected to surface fault traces.

臺灣北部中新世頭帕海膽化石及海膽富集帶古環境意義

A cidaroid (Echinodermata: Echinoidea) and three echinoid assemblages from the middle Miocene of northern Taiwan

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Abstract

Cidaroids (Echinoidea: Cidaroida) are the most basal taxa among extant echinoids. However, the relative scarcity of intact cidaroid tests in Cenozoic fossil records poses challenges for understanding their biogeographic patterns and evolutionary trends. This study reports an articulated cidaroid fossil recovered from the Middle Miocene Nangang Formation, representing the oldest occurrence of this order in Taiwan. The specimen exhibits transverse oval and confluent areoles, along with distinct, rod-like, spinose primary spines, suggesting that it belongs to the genus *Prionocidaris*. Moreover, the preservation of large primary spines still attached to the test is indicative of an obrution deposit. It is likely that the specimen was removed from its original reef habitats and transported into a depositional basin via a storm event. Within the 200-meter thick section, three distinctive echinoid assemblages are recognized, including Astriclypeoidea assemblage, Spatangoida assemblage, and Cidaroida assemblage. The potential paleoenvironmental implications and comparisons to widespread Miocene echinoid faunas of the circum-Mediterranean area are discussed.

Keyword: Cenozoic echinoids; paleoecology; taphonomy; Miocene; Nangang Formation

Miocene biogeography of keyholed sand dollars from Europe, India and Taiwan

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Abstract

Echinoids provide an enthralling avenue for the exploration of evolutionary histories. This study underscores the importance of employing morphometric analyses on specimens sourced from three diverse geographic regions such as Europe, India and Taiwan. Both traditional and geometric methodologies were used to refine our understanding of evolutionary relationships, emphasizing the need for a precise reconsideration of migration and evolution patterns within the Astriclypeidae family. The landmark analysis, a pivotal tool in this investigation, facilitated the comprehension of organismal variations based on morphology, relying on thoroughly prepared and accurately aligned photographs of the published specimens. Principal Component Analysis (PCA) conducted on the data obtained from both approaches revealed distinctive clustering for all the species considered. Notably, the Indo-West Pacific (IWP) and Taiwan specimens exhibited a closer phylogenetic relationship compared to those of Mediterranean origin. Strikingly, this closer relationship challenges the presumed link with Mediterranean origins, as indicated by Seilacher in 1990. The congruence in results from traditional and geometric morphometric analyses underscores the robustness of our findings.

Keywords: Morphometrics, Principal component analysis, Astriclypeidae, lunule variability, Miocene biogeography

台南龜丹溪剖面糖恩山砂岩之沉積環境

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摘　要

台灣全島西部麓山帶地質分區中分布最廣的淺海相砂質地層為晚中新世至早上新世的桂竹林層及其同時代的地層，相變也是最為明顯的，整體呈現沉積環境由北往南逐漸加深的趨勢。根據諸多前人研究，位於台灣北部至中部的桂竹林層，其相對應的地體構造特徵代表著北港高區以北前陸盆地的早期發育階段，但其同時期的糖恩山砂岩則代表著北港高區以南仍處於被動式大陸邊緣的沉積階段。為了明瞭兩者間沉積學上的差異，本研究選擇台南龜丹溪流域竹頭崎斷層上盤出露厚度約380公尺的糖恩山砂岩，進行地層柱及岩相學的建立與分析，另外再輔以生痕化石的觀察記錄，綜合探討本研究區域糖恩山砂岩之沉積環境的變化與沉積相的特徵，並且希望據此基礎，能更進一步討論地體構造的差異對沉積環境造成的可能影響。

由野外所辨識的岩相特徵可以分為1種泥岩相，2種粉砂岩相及3種砂岩相，而根據岩相組合，又可進一步細分成水道內沉積及非水道沉積兩種沉積特徵。本研究推測當時的沉積環境主要以暴風作用與疑似濁流作用為主的遠濱沉積體系。

從岩相組合可推測本研究區之厚層砂岩層是透過疑似暴風所引起的濁流順著大陸棚底部向深處搬運，將較粗顆粒沉積物帶至平均暴風浪基面之下堆積，並透過此過程產生海底水道及溢岸（overbank）或片流（sheet flow）等較細顆粒的非水道沉積物，整體沉積特徵類似於淺海濁流岩的特徵及機制。最後，藉由與前人研究的成果相比較，本研究區也推測糖恩山砂岩沉積時受正斷層作用影響，使得同時代的糖恩山砂岩沉積物所堆積的厚度由西向東逐漸增厚。

關鍵字：糖恩山砂岩、沉積環境、被動式大陸邊緣、淺海濁流岩

古亭坑層黏土礦物特徵與油母質類型變化之隱示

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摘　要

油母質類型為生油岩評估中一個重要的評估要素，其關係到生油岩產出的碳氫化合物種類(如 I、II 型油母質產油、III 型油母質產氣，以及 IV 型油母質不具油氣生產潛能等)。古亭坑層為臺灣西南部一巨厚的泥岩層，保存較完整的沉積紀錄，本研究以二仁溪東剖面的古亭坑層為研究對象，對該區域晚中新世至早更新世時期古亭坑層的黏土礦物特徵與油母質類型進行分析。藉由對比前開期間古亭坑層黏土礦物特徵與油母質類型於時間上的變化趨勢，以幫助我們了解當地層的沉積物逐漸轉變為以來自臺灣造山帶為主時，油母質類型將會產生何種變化。

本研究藉由 X 光繞射分析(XRD)與元素分析來分別獲得古亭坑層的黏土礦物特徵與油母質類型。在古亭坑層黏土礦物特徵方面，晚中新世至早上新世期間(約 5.60 Ma 至 3.50 Ma)的古亭坑層伊萊石與綠泥石含量較低；於晚上新世(約 3.50 Ma)之後，伊萊石與綠泥石的含量逐漸上升；而在約 1.80 Ma 以後，伊萊石與綠泥石的含量雖略為減少，但伊萊石的結晶度卻明顯變好，這暗示著於 1.80 Ma 以後，古亭坑層的沉積物以臺灣造山帶直接侵蝕而來為主。在油母質類型方面，晚中新世至早更新世期間(約 5.60 Ma 至 1.80 Ma)古亭坑層的油母質由以 III 型為主並開始逐漸偏向 III、IV 型混和；並於更新世早期(約 1.80 Ma)之後，古亭坑層的油母質類型轉變為 III、IV 型混合並開始偏向 IV 型油母質。

綜合上述，我們可知道當臺灣西南部地層的沉積物若為以來自臺灣造山帶為主時，地層中的油母質將會以較不具油氣生產潛能的油母質類型(即 III、IV 型混和或 IV 型油母質)為主。

關鍵字：古亭坑層、黏土礦物、油母質類型

利用浮游性有孔蟲比例推估臺灣西南部古亭坑層之古水深

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摘　要

古亭坑層保存較完整的古環境紀錄，前人曾以底棲有孔蟲的群落及沉積岩相等方式研究古亭坑層的古環境演化，多認為從古亭坑層底部至頂部的古環境水深為由深變淺，從上部亞深海環境逐漸轉為淺海環境。本研究以古亭坑層二仁溪東剖面之露頭樣本，進行浮游性及底棲性有孔蟲的數量計算，並使用 Tapia 等人(2022)以臺灣鄰近海域表層沉積物樣本建立的浮游性有孔蟲佔全部有孔蟲的比例(P%)與沉積水深的關係式，進行古水深的換算。結果顯示，二仁溪東剖面全段P%大約是在 35.4% - 97.8%之間，古水深換算結果落在 118-1,753 公尺深之間。晚中新世時期(~5.6-5.3 Ma)平均水深約為 1100 公尺，早上新世期間(~5.3-3.5 Ma)水深先快速變淺至約 500 公尺後，晚上新世至早更新世期間(~3.5-1.8 Ma)又變深至約 1000 公尺深，早更新世早期(~1.8 Ma)以後，水深則持續變淺至約 200 公尺深。將本研究古水深結果與前人研究比較，雖然以浮游性有孔蟲比例所求得的古環境水深都較前人記載的深，可能是由於現代的海洋環境背景(如溫度、鹽度等)與堆積古亭坑層時的環境有些許差異，造成偏差。但是本研究所得之整體水深變化的趨勢與前人相近，故仍具有其可信度。未來或許可利用底棲有孔蟲之群落分析，對經驗式做校正，以獲得研究區域較正確的環境水深。

依據本研究建立出的古水深變化趨勢，並參考前人對臺灣造山運動的研究成果，古亭坑層從晚中新世至早更新世期間的環境變化如下：晚中新世時應屬於亞深海環境；早上新世期間可能受到北部造山運動開始，地層抬升，沉積環境快速變淺；晚上新世至早更新世期間，因造山帶增高，地殼荷重逐漸增加，導致前陸盆地沉陷量變大，使研究區域的水深又增加；早更新世早期以後，造山帶越來越接近研究區域，堆積速率變快，盆地被快速填滿，沉積環境轉為淺海環境。

關鍵詞：古亭坑層、有孔蟲浮游底棲比、古水深

古亭坑層生物指標化合物揭示之環境變遷

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摘　要

台灣西南部泥岩區有油氣徵兆存在，因此過去一直有油氣探勘活動進行。而泥岩區中二仁溪東剖面的古亭坑層依據前人研究指出有相當連續之沉積序列，因此可作為探討古環境變遷與生油潛能的優良材料。本研究取二仁溪東剖面露頭岩石樣品，年代涵蓋晚中新世到更新世，並以氣相層析串聯質譜儀分析岩樣萃取物中的生物指標化合物探討古環境變遷。生物指標化合物中的類固烷與類萜烷化合物可反映有機物來源與沉積環境；結合這兩類化合物分析結果顯示古亭坑層以海相沉積環境為主，同時海洋生產力變化不大。而反映氧化還原的生物指標化合物則指出沉積環境自晚中新世到更新世整體有逐漸轉向還原的趨勢，且變化可能與構造活動有所關聯。特別在早上新世到早更新世期間因受造山影響，水深快速變淺又逐漸加深，沉積環境先趨向氧化再轉成還原狀態。而自早更新世以後，堆積速率變快，沉積環境逐漸變為較封閉的淺海環境，可能因此導致環境逐漸轉向還原狀態。本研究應用生物指標化合物結合其他地質資料探討古亭坑層沉積環境變遷，並應用於生油岩特性之評估。

早更新世古亭坑層裂星海膽化石及其古環境與地質意義

Schizaster fossils (Echinoidea: Schizasteridae) from the Gutingkeng Formation (Early Pleistocene) of Taiwan and its paleoenvironmental and geological implications

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Abstract

Schizasterids collectively represent a highly diverse group of irregular echinoids with abundant global fossil and extant records. Despite their wide distribution, poor preservation potentials associated with their delicate and thin tests have led to limited comprehensive studies of this fossil group in Taiwan. In the study, we report a new occurrence of *Schizaster* from the Gutingkeng Formation (Early Pleistocene). Despite the inherent fragility and pronounced deformations in the specimens, key diagnostic characteristics are preserved: heart-shaped test and deep ambulacrum III with regularly arranged pore pairs. These specimens also indicate the ecological dominance of *Schizaster* in fine-grained substrate environments, where its population density significantly exceeds that in coarse-grained high energy habitats, highlighting the *Schizaster* assemblages as potential biofacies indicators. Furthermore, the temporal and geographical distribution of these assemblages in Taiwan may be correlated with the orogeny history of Cenozoic Taiwan.

Keyword: Echinodermata; Echinoidea; paleontology; paleoenvironment; orogeny

桃園濱海地區兩口地質探井之地層沉積環境分析結果

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摘　要

台灣海峽與西部濱海地區之地質資料盤整與盆地分析為本公司近年之重點，本研究將針對海峽北段桃園-新竹之濱海地區進行分析，由於桃園地區新生代地層之沉積環境與層序地層分析大多仰賴西部麓山帶之地表地質分析結果，濱海地區之兩口地質探井可在地表地質資料缺乏之平原或濱海地區提供所需之井下電測、地層岩性、生物化石、沉積特徵等地質資料，本研究將根據井下資料判釋沉積環境並劃分層序，初步探討桃園濱海地區之沉積環境變遷與盆地演化歷史。

根據南港層沉積以來至今的沉積環境分析結果，井下資料可觀察到濱海地區之南港層與南莊層之地層特性與西部麓山帶出露地層類似；濱海地區桂竹林層沉積環境為濱面至外陸棚，與桃園地區西部麓山帶出露之桂竹林層明顯不同，並可在井下觀察到多層基性凝灰岩的分布，且層厚可達30公尺；錦水頁岩之層厚僅有100公尺，且多為泥質粉砂，未見厚層頁岩；卓蘭層下段以淺海之內遠濱環境為主，卓蘭層中段沉積環境快速轉淺，開始沉積濱海至陸相沉積物，應與東側造山帶剝蝕之沉積物輸入有關。

關鍵字：桃園濱海、地質探井、層序地層

The Morphological Change Of *Elphedium Advenum* Across The Cholan-Toukoshan Boundary In Miaoli, Taiwan

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Abstract

The Cholan Formation, characterized by repeated interbedded sandstone and mudstone layers, is one of the most representative Cenozoic formations in Taiwan. However, due to the similarity of the lithological characters between the Cholan Formation and the Hsianshan Sandstone Member of the Toukoshan Formation, the corresponding stratigraphic boundary in Taiwan is yet to be defined. While searching for the new Cholan-Toukoshan Boundary (CTB) on land, we noticed *Elphedium advenum* (Cushman, 1922) – a species of benthic forams - has a significant volume reduction across the CTB. Based on the new nanofossil evidence, this change is associated with a local extinction event that happened between nanofossil biozone NN19a and NN19c which may be caused by the glacial-interglacial cycle. While some former studies suggested the use of planktonic forams and nanofossils for defining the CTB, we observed that the amount of planktonic foram fossils is rare in the samples from the Cholan Formation. In addition, many microfossils show signs of reworking. Thus, the former interpretation based on planktonic foram biozones seems unreliable. Instead, the change of morphological characters of specific benthic foram may be a more feasible way to define the CTB in Taiwan.

老標本的大故事：早坂一郎典藏獸骨再研究
New story behind the old museum specimens: Restudy of bone collection of Hayasaka Ichirō

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摘 要

Based on the latest biographical literature on Professor Ichirô Hayasaka (1891-1977), unlabeled animal bones stored in the Department of Geosciences of National Taiwan University (NTUG) are re-examined. Primary study materials consist of three animal, skeletal parts: a skull of Felidae, a complete set of left forelimb bones of Felidae, and a complete set of left hind limb bones of Ursidae. Preliminary findings suggest that these specimens were part of the animal remains distributed to Professor Hayasaka by the Taiwan Governor-General's Office when orders were given to execution of beasts in the Yuanshan Zoo (The Predecessor of Taipei Zoo) during the Second World War (WWII). In this study, we aim to use Morphometrics to clarify the species of these three animal bones and compare them with the published data. If the proposed research can confirm the hypothesis, the archived specimens will be the earliest surviving skeletal evidence of exotic, large carnivores reared in Taiwan. It will also be the only remaining evidence of the animal execution at Yuanshan Zoo during the WWII.

Keyword : Ichirô Hayasaka、Felidae、Morphometrics、WWII、Taihoku Imperial University

河南商丘商朝晚代遺址的碳十四定年：以考古定年佐證台大碳十四定年的可靠性

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摘　要

中國河南安陽有兩處重要的商代考古遺址。一處是安陽殷墟，被認為是商朝晚期（約西元前 1146~1046 年，此處的年代資料無法直接對應 ^{14}C 年齡。參見“夏商周斷代工程”）都邑；另一處是殷墟東北外緣的洹北商城，被認為屬商王朝中期。前者出土了大量青銅器、玉器，也發掘出商代戰馬車（現保存於中國南方科技大學考古博物館）；後者發現了較完整的城郭遺址、也發現宮殿以及集中存在的作坊。本研究是針對兩處遺址的一次年代學驗證。我們分別對殷墟馬車中的馬骨、人骨和殷墟遺址的人骨和牙齒，以及洹北商城出土的動物骨骼和碳屑樣品進行了碳十四定年，以檢驗中國考古學界此前給出的商中期、商晚期排序，同時對二者的年代範圍作出更嚴格的年代框定。

對骨頭樣品同時進行骨膠原和骨粉的有機碳定年，比較兩者的年齡差異。首先，從洹北商城考古遺址採集的 4 個碳屑樣本的校正 ^{14}C 年齡在 3185±190 至3320±150 cal yr BP, 平均為 3275 cal yr BP, 重量加權平均為 3285 cal yr BP。這些碳屑年齡與從相同地點採集的動物骨頭中提取的骨膠原的 ^{14}C 年齡相近，後者的年齡分別為在 3240±165 和 3350±145 cal yr BP, 說明這兩個骨頭樣本的 ^{14}C 年齡沒有受到外來碳的影響。骨膠原樣本的 C/N 比值（3.18～3.25）也說明骨頭保存良好。通常認為 C/N 大於 3.3 指示骨膠原受外來有機質的影響。從博物館戰車中採集的人骨和馬骨的 ^{14}C 年齡在 3065±190 至 3950±140 cal yr BP，骨膠原樣本的C/N 比值為 3.36～4.03，C/N 比值越大，年齡越老，說明這些骨膠原 ^{14}C 年齡受到外界碳一定程度的影響。

定年結果顯示，從洹北商城考古遺址得到的 ^{14}C 年齡老於殷墟考古遺址得到的 ^{14}C 年齡，顯示洹北商城考古遺址早於殷墟考古遺址。本實驗室的骨膠原和碳屑 ^{14}C 年齡均接近商朝晚期，顯示本實驗室的定年質量可靠。另外，骨膠原 ^{14}C 定年通常比骨頭中的總有機碳（TOC）可靠，因為後者會因外界有機碳加入埋藏的骨頭中而受到污染。提取骨膠原一方面是一個艱難的過程，另一方面需要較大的樣品量，很多風化強烈的骨頭無法提取骨膠原。本研究的 6 組定年數據對比，顯示骨膠原與骨粉 TOC 的年齡相差 3%～25%。在無法提取骨膠原的情況下，骨粉TOC 可以給出一個參考年齡。

利用穩定碳同位素與矽藻紀錄重建台灣東北部山區全新世水文氣候變遷

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摘　要

為重建臺灣東北部古氣候與推演古環境，選擇位於海拔 2100 公尺的宜蘭三星妹池作為研究地點，該地區降水主要源自春夏之際的梅雨、夏季的颱風和冬季的東北季風。於三星妹池水深約 50 公分處，採集長 250 公分的沉積物，並進行 Pb-210 和 C-14 定年。結果顯示本岩心約包含 11000 年以來的紀錄。研究方法包括分析穩定碳同位素、粒徑及矽藻資料。沉積物內有機物物質以 EA-IRMS 進行分析得出碳氮比 (C/N)、總有機碳量 (TOC)、δC-13 的結果，而矽藻分析則於光學顯微鏡下進行鑑定與計數。穩定碳同位素資料則基於全新世的早期 (11650-8186 cal BP)、中期 (8186-4200 cal BP)、晚期 (4200cal BP 至今)進行分區。三星妹池 (SXMP)整體較輕的δC-13 值落於代表木本、喬木的 C3 植物範圍，與花粉紀錄中高木本植物比例相符合。在 8000-10400cal BP 期間，TOC 含量和碳氮比高，8000 cal BP 後碳氮比逐年下降，3410-790 cal BP，較高的 TOC 和較重的δC-13 可對應到全新世晚期變冷事件，自 790 cal BP 以來，碳氮比降到歷年最低，而 TOC 和δC-13 出現小幅上升。矽藻僅保存於上部 50 公分（480 cal BP），種類以底棲型的短縫藻屬 (*Eunotia*)為主，代表沉積環境呈現酸性，並且是低水位的狀態。

台灣東北部山區小冰期時的水文氣候變遷

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摘　要

鴛鴦湖位於海拔1620公尺之日本柳杉人工林中，直至1963年森林開發處開闢100線森林線道時發現此湖後，於1969年設立為自然保護區至今，過去未受人類擾動。

本研究分析台灣北部棲蘭山區鴛鴦湖沉積物內矽藻化石與有機物之TOC、TON、TOC/TON比、δ^{13}Corg(‰)與碳屑紀錄，重建近600年來，水文氣候變遷對當地森林與水域生態系之影響。本研究使用長40公分之短岩芯(YYL20-1)，基於Pb210與C14之定年結果所建立之年代深度模式，此岩芯包含過去600年古環境記錄。研究結果顯示此區域之三個主要環境變化階段：小冰期早期、小冰期晚期與人類開發階段。第一階段為小冰期早期，其TOC與TOC/TON比值呈現穩定狀態，炭屑紀錄顯示有森林火災事件，顯示此時期為乾燥氣候；第二階段為西元1510~1900年間，於1560年可看見TOC急遽增加、δ^{13}Corg(‰)變重，反映出湖中有機質沉積物增加，推測有一強降雨颱風事件將大量TOC之物質沖刷至湖中沉積；第三階段為西元1900~2020年 ，TOC於此階段有兩次增加，對應人類於周圍山林兩次開發對其沉積環境之影響。

以花粉紀錄重建的台灣中部全新世環境史

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摘　要

因應高解析度古氣候資料的需求，本研究分析採自台灣中部頭社盆地內長8公尺之泥炭岩心，由於本研究擬針對全新世大暖期其時間分佈與氣候狀態進行確認，因此僅分析岩心之上部6公尺，其時間包含11000年以來的紀錄。為能提高花粉紀錄時間解析度，本研究以2公分間距取樣，並進行連續樣本的花粉分析，以重建頭社盆地全新世的植群變化歷史，藉由冷暖花粉種類的消長情形，推估頭社盆地的古氣候變遷。

根據穩定碳同位素資料顯示，全新世以來可區分為3個區域，分別是全新世早期(11700-8200 cal BP)、全新世中期(8200-4200 cal BP)、全新世晚期(4200-1800 cal BP)。而在11700 cal BP時，頭社盆地可以很好的對應到早全新世時期的初期階段，且在陸生植物為主的環境下，從木本植物轉換成以草本植物為整個時期的主要優勢植群。雖然在全新世早期(11700-8200 cal BP)和全新世中期(8200-4200 cal BP)的階段可以看出各數值較大幅度的波動變化，但其中存在的差異現象，也都還在合理變化範圍內。

目前初步已知的孢粉化石鑑定結果為84種分類單位，而其中以草本植物禾本科(*Poaceae*)、艾屬(*Artemisia*)，濕地植物莎草科(*Cyperaceae*)，木本植物櫟屬(*Quercus*)/青剛櫟屬(*Cyclobalanopsis*)、苦櫧屬(*Castanopsis*)/柯屬(*Pasania*)、柳屬(*Salix*)，蕨類孢子為主要優勢化石。

關鍵字：頭社盆地、全新世、孢粉、穩定碳同位素、氣候變遷

恆春頭溝巨大鬚鯨化石的埋藏與發掘

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摘　要

截至目前的臺灣古生物史上，計有三次大型古生物的發現。首次大型古生物發掘，為1971年化石蒐藏家潘常武與陳世卿先生於臺南左鎮菜寮溪發現的早坂氏島犀（*Nesorhinus hayasakai*），由臺灣省立博物館及日本學者鹿間時夫合作將化石全數運回，惟標本現已散落各地且難以追溯。第二次大型古生物發掘，為2006年於澎湖群島內垵海岸由當地居民發現，後交由國立自然科學博物館進行修復及研究的潘氏澎湖鱷（*Penghusuchus pani*），是迄今於臺灣與周邊地區發現的最古老脊椎動物化石。第三次大型古生物發掘，為2022年由國立自然科學博物館團隊於恆春西臺地的頭溝發現的大型鬚鯨化石，為目前臺灣發現最大、最完整的脊椎動物化石。臺灣過往的脊椎動物化石發現，多源自於河床撿拾或澎湖水道海底打撈的標本，樣本較零散破碎，也缺乏原地層相關資訊。本次於頭溝發現的鬚鯨化石身長約18公尺，年代為11萬年前至8萬3千年前，為原地埋藏。不僅完整保存近八成的骨骼，各部位從頭骨至尾椎骨皆呈原位排列，且前肢的掌骨及腕骨亦呈現原位埋藏，為臺灣古生物發掘史上可遇而不可求的標本。

Plio-Pleistocene exhumation of the Hsuehshan Range: Constraints from new detrital zircon U-Pb ages of foreland basin sediments.

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Abstract

The Taiwan mountain belt experienced a significant tectonic uplift during the Plio-Pleistocene, shaping the present-day geology of the Hsuehshan and Central Ranges. The western foreland's sedimentary sequences, deposited during this topographic build-up, offer a continuous record of adjacent mountain exhumation. In this study, we aim to constrain the timing of surface exposure and erosion of the major geologic units of the Hsuehshan Range through the study of its erosive products. We conducted U-Pb dating of detrital zircons of 23 samples from different stratigraphic sections of the foreland basin including the Chinshui, Cholan, and Toukoshan Formations (bottom to top).

The majority of the samples indicate that the age distribution of younger sediments spans from Miocene to Eocene (13-42 Ma) across all formations. Meanwhile, the maximum population ranges from Cretaceous to Jurassic (120-200 Ma), with differing proportions of grains exhibiting Neoproterozoic to Paleoproterozoic ages (700-2800 Ma). Based on our new data, the waning of exhumation in the Hsueshan range is recorded on the Plio-Pleistocene sedimentary rocks and is characterized by the decrease to total disappearance of Paleoproterozoic and Neoproterozoic peaks. The most pronounced shift in sediment source is observed between the Late-Pliocene-Early Pleistocene Cholan Formation and the Early-Late Pleistocene Toukoshan Formation. The drastic disappearance of Proterozoic peaks on the Toukoshan formation is accompanied by a pronouncement in the Jurassic age peaks supporting a change in the sediment source during the terminal stage of exhumation in the Late Pleistocene.

Keywords: U-Pb dating, Toukoshan Formation, Cholan Formation, Chinshui Shale.

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Keywords: U-Pb dating, Toukoshan Formation, Cholan Formation, Chinshui Shale.

2022 年關山—池上地震後玉里地區的跨斷層地表破裂錯移量變化

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摘　要

2022 年關山—池上地震發生後的數個月間，玉里鎮中心橫跨同震破裂跡的民宅與路面在反覆修補後仍持續破壞，顯示該地區可能受到近地表震後變形的影響。為了解該區地表破裂的活動特性，本研究自地震後即開始在人工構造物多且修補較頻繁的玉里鎮中心區域進行多次實地測量，並透過照片測量得到同一指標累計錯移量隨時間變化的數值，以了解該地區跨斷層的震後變形以及其隨時間的變化。

本研究在玉里鎮區的測量結果顯示，2022 關山—池上地震後所量得的同震跨斷層錯移量約在 7 cm – 20 cm 之間，且透過照片測量與野外測量的比較可發現其變形的行為有明顯的近斷層撓曲發生。跨斷層錯移量在地震發生兩個月後明顯較同震錯移量增加約 5% – 60%，且震後三個月的測量成果亦較先前的錯移量增加約 0 – 15%，顯示該地區地表跨斷層破裂的震後變形有明顯隨時間而減少的趨勢。在 2023 年 1 月之後的野外調查亦顯示部分調查點地表仍有持續破壞的發生，代表該地區近地表的震後變形的行為延續超過三個月以上。

綜合以上野外實際的測量成果，本研究發現該地區北側同震錯移量最大的玉里醫院在三個月內的震後變形可達同震跨斷層錯移的 25%，而其他跨斷層同震錯移較小的測量目標，其震後變形對同震錯移的比例高於 40%。此一結果暗示跨斷層同震錯移較小的目標可能有伴隨較大的近地表震後變形，使總跨斷層錯移量趨近一個定值。此一結果可能反映了未固結沉積層受變形後的塑性變形特徵，以及發震斷層淺部的震後滑移。

關鍵字：2022 關山—池上地震、同震錯移、震後變形

Keywords : 2022 Guanshan-Chihshang earthquake, Coseismic slip, Postseismic deformation

臺灣活動構造三維數值模型資料庫更新（2024年版）

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摘　要

活動構造三維數值模型資料庫乃是國家災害防救科技中心與國立臺灣大學、國立成功大學及臺灣中油合作，透過三角網格面建構地下活動斷層面的形貌。經過多期的建構工作，目前全臺多數之活動斷層皆建構有初版模型，並透過GOCAD軟體進行斷層參數計算，同時逐年利用地震序列修正斷層模型型態。在本年度的工作中，本研究利用近年來發生於花東縱谷西翼一連串的逆衝斷層事件、包含2022年關山—池上地震序列，並參考陳文山等（2018）的論述，將中央山脈斷層由北至南分為五個區段；也透過2022年關山—池上地震事件地表破裂跡，搭配同震時斷層的地表錯動型態，完成玉里斷層的三維數值模型建構。

關鍵字：三維地質構造數值模型、中央山脈斷層、玉里斷層

Keywords: 3D Geological Structure Model, Central Range Fault, Yuli Fault

The Application of the Disaster Images on the Survey of the Surface Ruptures of the 2022 Chihshang Earthquake in the Yuli Township

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Abstract

The 2022 M_L 6.8 Chihshang Earthquake (0918 Earthquake) occurred in eastern Taiwan and induced the surface ruptures along Yuli Fault and Chihshang Fault. The coseismic displacement along Yuli Fault displayed apparent left-lateral slip movement mainly. The surface ruptures across the downtown of Yuli Township and induce the road cracks and building damages, which indicated the movement information of fault and usually be restored soon. The method that delineate the rupture locations or measure the rupture displacements rapidly are necessary. However, the investigators often can't arrive to the field and record these phenomena after earthquake immediately. The immediate on-site images often exposed by disaster relief works or the reporters of mediums, that may imply geological information.

Even though there are convenient tools such as drones, smartphone, or GPS positioner which applied in the work of survey recently. In order to describe the trace of surface ruptures immediately, some off-site methods should be trying. In the downtown, the buildings, sidewalks, street nameplates, and other artificialities are easily recognizable reference points. Therefore, we try to use the images after earthquake in the Yuli area and compared the reference points in the field. The location of rupture traces truly can be well defined by compared the intersections of the artificialities or reference points on the map. The demarcated rupture traces reveal the usability because the results are consistent with the measurement of GPS tools. In fact, the on-site images provide useful and definite space information which can be applied on the remote surface ruptures survey.

利用正斷層上盤滾動背斜形貌建立山腳斷層二維地下幾何

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摘要

臺灣位於地震頻仍的板塊交界帶，斷層遍布全島，為了瞭解斷層的活動潛勢，本計畫蒐集資料並擬定斷層幾何，本研究的目的為瞭解山腳斷層的地下幾何形貌。山腳斷層為鏟型的正斷層，臺北盆地位於山腳斷層的上盤，盆地中更新世沉積物在靠近地表斷層跡的區域厚度較厚、深度較深，遠離地表斷層跡的沉積物厚度較薄，深度較淺，地層深度分布呈現滾動背斜（rollover anticline）剖面的特徵形貌。本研究根據前人建立的台北盆地地層深度剖面圖，以更新世沉積物與第三紀基盤間的不整合面為指準層，並以線平衡原則恢復地層長度，推估拉張量約為 210 公尺。

本研究進而利用美國油公司發展的雪佛龍建立法（Chevron construction method）嘗試建立山腳斷層的地下幾何形貌。雪佛龍建立法為根據滾動背斜的剖面建立鏟型斷層形貌，此方法主要考量斷層發育的過程中，斷層上盤的水平拉張量（heave）為固定，而垂直位移量（throw）隨著斷層角度的變化而改變。本研究假設拉張距離為 210 公尺，利用雪佛龍建立法建立山腳斷層幾何，則斷層淺部約為 68 度傾角，深部漸漸轉為 33 度傾角，斷層底部深度可達 15 公里左右。

關鍵字：斷層幾何、山腳斷層、雪佛龍建立法、臺北盆地

烏山頭斷層南段構造特性與活動性調查

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摘　要

烏山頭斷層（又稱崙後斷層）為臺灣南部重要的逆移斷層，呈東北走向，北起嘉義縣觸口東側，為獺頭斷層所截，朝南南西延伸經關子嶺東側，連接（或截切）觸口斷層，最後在台南市左鎮區松仔腳地區為左鎮斷層截切或連接新化斷層，長度約50公里。陳文山（2003）提出烏山頭斷層為分隔內外麓山帶之重要界線，並可能具有活動性；而烏山頭斷層上盤發育的背衝斷層－口宵里斷層，也經調查證實其活動性，並列入地礦中心新公布的活動斷層（林啟文等，2021）；且在烏山頭斷層至口宵里斷層間為一快速抬升區域，顯示烏山頭斷層應具有活動性。由於烏山頭斷層南段出露較完整，且南端尚殘存階地堆積層覆蓋於斷層帶上，本研究透過此區域之地質調查與鑽探以了解其構造特性及是否具活動證據。

本研究調查區域北起南174市道，南抵左鎮區松仔腳，烏山頭斷層上盤在此區域最北為糖恩山層，下盤為或沄水溪層或六重溪層，往南斷距逐漸減小，上盤逐漸轉為鹽水坑頁岩直至北寮層甚至是六雙層，下盤也由六重溪層轉為二重溪層、六雙層與階地堆積層；斷層面則由向東傾斜35-70度，逐漸降低至20-40度；其下盤發育約略與之平行延伸的烏山頭背斜，背斜核心出露沄水溪層，該背斜在走馬瀨南側尖滅，或被烏山頭斷層所掩覆。在此區域烏山頭斷層出露良好，在走馬瀨以南到松仔腳之間甚至可連續觀察追蹤，並在最南端出現一延伸近1公里的線形崖，線形崖略轉為東北－西南走向。

上述線形崖延伸至菜寮溪畔階地受到侵蝕消失，但階面仍殘存階地堆積層，地礦中心委託黎明工程顧問公司，在此階地施行跨線形崖延伸區域的排鑽，結果顯示在早於1萬年至約2萬年間，約更新世晚期至全新世早期的沉積物，普遍受到斷層錯動並發育寬廣的斷層帶，顯示烏山頭斷層為更新世晚期（距今約100,000年內）曾經活動過的斷層，屬於第二類活動斷層。

鼓山斷層構造特性與活動性調查

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摘　要

鼓山斷層位於臺灣南部，為逆移斷層，呈東北走向，北起高雄市旗山，可能為木柵（平溪）斷層所截，向西南延伸經旗山區擔橫山，南端在田寮區併入車瓜林斷層，長度約11公里。鼓山斷層東側鄰旗山斷層，西側為車瓜林斷層，後二者在近幾年研究已確認屬活動斷層，局部具潛移特性，推論鼓山斷層可能也具有活動性，本研究進行調查以確認其構造特性與是否具活動證據。

鼓山斷層上下盤皆為古亭坑層，有數處良好剖面可觀察追蹤，其斷層帶僅約數公尺至十餘公尺厚，斷層帶內剪切程度並不高，鱗片狀葉理往往僅數毫米至釐米厚，其餘為穿入層間與裂隙的泥流及受拖曳岩層，在不同剖面所見的斷層特性也有相當差異：鼓山斷層北段上盤岩層位態呈背斜形，因此過去有部分調查也以鼓山背斜稱之；中段局部伴隨著因層間滑移分離而產生小規模而延伸不遠的背斜、向斜與斷層；南段則以斷層帶為主。

在旗山市區西側的鼓山斷層上盤，分布一片階地礫石層，以交角不整合覆蓋於古亭坑層上，階地礫石底部碳樣定年為6330 +/- 30 yr BP，因受鼓山斷層活動抬昇，階面已向東反向傾斜超過7°，顯示鼓山斷層於全新世曾活動過。

The Implications of the Surface Ruptures Occurred during the 2016 Meinong Earthquake in Tainan Area, Southern Taiwan

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Abstract

The Meinong Earthquake occurred on February 6, 2016 around Tainan area, southern Taiwan. The epicenter of this magnitude 6.6 earthquake was located in the Meinong District, Kaohsiung City. The intense coseismic ground acceleration induced construction damages which located in Tainan area. In addition, numerous surface ruptures were also observed in this area. In Hsinhua and Guanmiao area, most of these ruptures were linear, and the strike of ruptures parallel respectively to the Hsinhua Fault and Guanmian syncline. Most of the ruptures caused of landslide or edge collapse. The types of surface ruptures can be divided into uplift ruptures on the slope, unilateral subsidence ruptures, compression uplift or tension crack caused by block rotation, and translation derived ruptures.

The 2016 Meinong earthquake was caused by a deep structure with a depth of over 10 kilometers, and its westward slip affected shallow folds or faults, or trigger the activities of these shallow structures. The coseismic displacement or related phenomena such as ruptures, sandboils or deformation occurred along the faults and fold structures under the influence of earthquakes. The surface ruptures with linear distribution occurred during significant earthquake were considered to be associated with fault easily. While the directions of these ruptures were associated with structures, the causes of these ruptures and their geological significance should be examined thoroughly and verified cautiously so as to provide accurate and comprehensive geological information.

玉里斷層活動斷層地質敏感區

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摘要

玉里斷層為臺灣東部重要的活動斷層之一，為左移斷層兼具向東逆衝分量，是 1951 年 11 月 25 日縱谷中部地震之地震斷層，屬於有歷史地震紀錄的地震斷層，當時地震造成之地變有斷層、地裂及地陷等現象，最大水平錯距約 1.6 公尺，最大垂直位移約 1.3 公尺。1951 年地震地表破裂穿過玉里國民學校造成南側地表破裂以 N10°E 方向。

2022 年 9 月 18 日東部地區發生規模 6.8 之關山地震，再度造成玉里斷層地表破裂，左移分量最大約 100 公分，抬升量最大約 100 公分。大地測量結果顯示同震最大垂直位移為震央東北側的花蓮卓溪古風國小（GE53 測站），垂直抬升 97.5 公分。

若再次發生活動，恐威脅人民生命財產安全，並造成重大經濟損失，因此，在綜合考量下，將玉里斷層列為地質敏感區。玉里斷層活動斷層地質敏感區位於臺灣東部縱谷中段，呈北北東走向，由花蓮縣玉里鎮大禹里向南延伸至富里鄉東里村，長約 14.6 公里。

關鍵字：玉里斷層、活動斷層地質敏感區、1951 年地震地表破裂、關山地震

Active Faults Monitoring in Taiwan

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Abstract

In order to understand the crustal deformation pattern, analyze anomalies for earthquake precursor and realize the activities of active faults, the Central Geological Survey and Mining Management Agency(GSMMA) has established an island-wide active fault observation network of GNSS and precise leveling stations in Taiwan. We referred the experiences on earthquake probabilities model and tried to apply it in Taiwan to calculate probabilities for potential earthquake of active faults.
On the part of integrated monitoring data, we combined several GNSS stations around active faults into triangles to calculate GNSS strain and analyze the results. Furthermore, we use the GNSS, precise leveling and PS-InSAR data to make velocity profiles across 33 active faults in Taiwan. On the part of earthquake probabilities analysis, this research evaluated the slip rate and slip deficit rate of active faults by 3 kinds of models(BLOCKS, DEFNODE and Baseline Inversion model). The acquired data were provided to assess fault parameters, and calculated recurrence intervals and occurrence probabilities of active faults. Only if we continue implementing the survey project, we can turn the long-term geodetic data into useful information for disaster prevention and reduction.

Keywords: crustal deformation, analyze anomalies, GNSS, precise leveling, PS-InSAR

Recent Developments in Active Fault Investigation in Taiwan

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Abstract

Locating in an ongoing orogenic belt (Ho, 1986; Teng, 1990), there are frequent seismic activities and many active faults in Taiwan. Large earthquakes are usually accompanied with the recurrent movement of active faults, which may cause surface fractures and severe hazards (Bonilla, 1977; Hsu and Chang, 1979; Yang, 1986; Tsai *et al*., 1998). Before 1990s, there were only sporadic studies about active faults with small scale map in Taiwan by scholars (Bonilla, 1977; Hsu and Chang, 1979; Yang, 1986). After the Kobe Earthquake happened in 1995 in Japan, some researchers were aware that the study on active fault was a critical issue also in Taiwan and called to speed up the relative studies.

The first program is proposed in 1997 and started the systematic investigations of active faults. The 1999 Chi-Chi earthquake is a key event and also a turning point in earthquake geology studies in Taiwan. In the past 20 years, active fault information has produced and is valuable to scientific research, construction and land use. The 36 active faults with surface length longer than 5 km are identified and shown in the 2021 edition which includes 3 new active faults. The 3 new active faults are Chuhsiang Fault, Kouhsiaoli Fault, Chekualin Fault, which are located in Nantou County, Tainan City and Kaohsiung City respectively. Our current works focus on delineation of active fault Geologically Sensitive Area (GSA). We announces 22 active fault GSAs from 2014 to 2023.

Keywords: active fault, hazard, Geologically Sensitive Area (GSA)

Normal fault growth models of Penghu Basin in W. Taiwan Strait and their implications for basin evolution

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Abstract

The growth of normal fault systems affects the development of rift basins. Fault systems could grow via segments developing independently (the so-called non-coherent model) or merge into one fault (coherent model). Also, they could experience decreases in fault system lengths, called lateral tip retreat, during the later fault-activity stage. In this study, we investigate the fault growth model by studying the Penghu Basin, a Paleogene rift basin in the western Taiwan Strait, and test the current fault growth models. Our methods include seismic interpretation and fault growth analyses, such as the spatiotemporal distribution of cumulative throw and throw increment. In the Penghu Basin, the boundary and transfer fault systems grew via the non-coherent model followed by lateral tip retreat, while other studied fault systems grew via the coherent model before their tips retreated. Furthermore, segments could separate from their parent fault systems prior to the lateral-tip-retreat stage. Our results also indicate that the specific rift phase of basin evolution is highly correlated with the development of fault systems. We suggest that the lateral tip retreat of fault systems marks a change in the rift phase of a basin and implies the end of basin evolution.

Key words: Penghu Basin, Fault growth models, Lateral tip retreat

On the discrepancy of rates between geological slip and geodetic shortening: A structural geometry viewpoint

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Abstract

The discrepancy between geological or geomorphic slips and geodetic shortening rates, commonly referred to as a slip rate deficit, is used as a metric of seismic potential for a given fault system under an assumption of an elastic Earth. Additionally, the discrepancy can be caused by other factors, including uncertainties in estimating both geodetic shortening and geological slip rates. Less attention has focused on uncertainties of fault geometry, on which geological slips are conversed based. Here, I demonstrate on examples from the Himalaya how not considering structural geometry at depth or basing results on uncertain fault geometry near the surface affects estimates of geological slip rates, and thus contributes to discrepancies between geodetic shortening and geological slip rates. I first show that duplex kinematics at midcrustal depth of the Central Himalaya can reduce transferred slip. This reduction leads to lower frontal geomorphic slip rates by at least ~10% -20% compared to expected rates inferred from geodetic shortening rates. Such internal shortening thus could potentially explain the discrepancies between the geodetic shortening rates across the Himalayan wedge and the geomorphic slip rates in the frontal Himalaya (Hu and Stevens, 2022). Second, I show how differences in interpreted fault geometry from a seismic image can affect the following estimates of geological slip rates and dependent conclusions. A case from the Central Himalaya illustrates that a minor difference in estimates of the total slip of a given structure could lead to up to ~10 mm/yr difference in the estimated geological slip rate. This difference in interpretation and thus estimates of geological slip rates could simply originate from applying different guiding models, limited quality of seismic images, or subjectivity (Hu, 2022).

Revisiting the Taiwan-Luzon Arc: Geochemical and Geochronological Constraints

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Abstract

The Taiwan-Luzon arc (TLA), or simply the Luzon arc, stretches from the Coastal Ranges of Taiwan to Mindoro Island in the Philippines. This arc formed as a consequence of the subduction of the South China Sea (SCS) crust along the Manila Trench, starting from the late-middle Miocene to the present day. The TLA is divided into five segments based on geographic location: Taiwan, Babuyan (islands offshore north of Luzon), Northern Luzon, Bataan, and Mindoro. Previous works on the TLA primarily focused on magmagenesis, particularly examining the influence of varying slab inputs on arc magma outputs. These efforts were concentrated on individual segments rather than providing a comprehensive understanding of the entire system. Therefore, our goal is to present a holistic view of the TLA subduction system by incorporating current geochronological and geochemical data, examining how it aligns with existing models for arc magmatism. The Sr-Nd isotope systematics in the northern and southern extremities of the TLA appear to be largely controlled by either sediment inputs from continental terranes or the composition of the subducting slab (normal oceanic crust/hyper-extended continental crust). In both cases, increasing continental input is reflected through time although the mechanism for the incorporation/influence of continental sediments or continental fragments is still debatable. Another intriguing observation in the TLA is the more primitive signatures in Northern Luzon, which seem to increase as the samples get younger. The current explanation for this phenomenon is the hypothesized slab tear beneath this segment, which could have facilitated the influx of primitive mantle material, resulting in the observed isotopic signatures. However, an alternative explanation suggests the presence of an unusual mantle component beneath.

南海東北部揭陽凹陷多期正斷層發育的構造型態及演化

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摘要

揭陽凹陷位於南海北坡，珠江口盆地東側，台南盆地南部凹陷西側，大致上位於大陸棚過渡到大陸斜坡的位置。此區域於中生代晚期至古近紀早期地殼張裂時期發育一系列東北-西南走向的半地塹構造，其後在新近紀期間亦發育另兩期正斷層，在這兩期正斷層發育之間被一後張裂期侵蝕面分隔。本研究的主要目的在探討多期正斷層以及侵蝕面在多期張裂的環境中的發育順序，每一期正斷層的空間分布特性，以及年輕斷層的發育受前期構造影響的關聯性。

揭陽凹陷內的正斷層可分為三種：T1，為半地塹的正斷層，此種斷層僅切過前張裂期以及同張裂期地層；T2，為僅發育於後張裂期地層的正斷層；T3，為切過同張裂期以及後張裂期地層的斷層。本研究又將 T2 斷層分為兩類：第一類為發育於半地塹上方，且被後張裂期侵蝕面截切的斷層；第二類為發育於侵蝕面之上，規模較小的斷層。T3 斷層也分為兩類：第一類為同張裂期發育的斷層於第二期張裂再活動且和發育於後張裂期地層內的斷層相連後繼續活動所形成；第二類為第二期張裂所發育的斷層向下切過同張裂期地層。

在空間的分布上，T1 斷層為東北-西南走向，形成各個大小不一的半地塹；T2 斷層大多發育在遠離大陸棚的位置；T3 斷層大多分布在研究區域東北側與西北側，接近大陸棚的位置，且大多被侵蝕面所截切。

由以上結果，本研究認為：在中生代晚期至古近紀早期，南海北坡經歷西北-東南向的張裂作用；在古近紀末，張裂作用停止，形成分離不整合面；接著在新近紀時期又經歷了第二次的張裂活動，而此次的張裂作用為西北西-東南東向；之後出現的侵蝕面將第一類 T2 斷層和 T3 斷層上部截切，並在侵蝕面之上形成新的地層，隨後在新地層發育第二類的 T2 斷層。

關鍵字：揭陽凹陷、正斷層、多期張裂、侵蝕面

台灣中部上-更新世前陸盆地沉積物來源與造山帶剝蝕歷史研究：麓山帶碎屑鋯石核飛跡與鈾鉛雙重定年分析

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摘　要

在造山運動過程中，造山帶的碎屑沉積物被剝蝕傳輸至前陸盆地。在台灣，造山作用隨時間的發展過程中，剝蝕的岩層由沉積岩逐漸轉為變質岩並沉積至前陸盆地。鋯石核飛跡為低溫熱定年系統，可以反映造山帶岩層被深埋的溫度及抬升時冷卻的年代，因此當沉積物沉積至前陸盆地時，分析盆地碎屑鋯石核飛跡定年可以反映山脈剝蝕隨時間的變化。鋯石鈾鉛定年由於具高溫的封存溫度，不易受後來的變質作用影響，因此在沉積盆地中鋯石鈾鉛年代譜可以反映來源區的岩層特性。

本研究分析台灣中部前陸盆地中，岩層的鋯石核飛跡定年及鈾鉛定年的雙重定年，藉此分析來源區中部雪山山脈剝蝕歷史。

本研究分析台灣中部烏溪流域上新世的錦水頁岩、更新世的卓蘭層與頭嵙山層的沉積岩。根據碎屑核飛跡定年結果，由錦水頁岩到卓蘭層中部，鋯石核飛跡年代顯示以未癒合年代為主。在卓蘭層上部到頭嵙山層之間，鋯石核飛跡年代轉變為部份癒合年代群，在頭嵙山層香山相開始出現小於 6.5Ma 的鋯石核飛跡年代。碎屑鋯石鈾鉛定年結果顯示，沉積物來源由錦水頁岩到頭嵙山層香山相之間，由年代譜顯示沉積來源由漸新世、中新世地層轉為始新世地層。由雙重定年結果得知，核飛跡年代小於 65Ma 的鋯石並非新生代火山活動的產物。本研究進一步分析核飛跡年代峰值與沉積地層年代的關係，滯後時間在 1.1~0.5Ma 快速縮短，顯示來源區崛起速率處於加速狀態。本研究最後將核飛跡年代分佈特性與西部麓山帶內不同地區之研究結果進行比較，癒合帶出露的時間以濁水溪流域最早，烏溪較晚。

由碎屑鋯石的鈾鉛定年與核飛跡定年得知，沉積物來源逐漸改變由未變質的中新世地層到淺變質的漸新世到始新世地層，在頭嵙山層香山相時，開始剝蝕變質度較高的始新世地層。在 1.1~0.5Ma 造山帶抬升速率由 974m/m.y.加速至 1196m~1286 m/m.y。鋯石完全癒合帶出露時間以濁水溪流域的 1.6Ma 最早。

關鍵字：前陸盆地、核飛跡定年、鈾鉛定年、滯後時間、剝蝕

利用地質剖面探討台灣中西部麓山帶的構造特性

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摘要

1999年台灣中部的集集地震，車籠埔斷層沿線形成約100 公里的地表破裂，過往研究發現，於濁水溪流域斷層崖高較鄰近區域高，並認為車籠埔－大尖山斷層在濁水溪南北兩岸的構造形貌有所差異：濁水溪以北，前人認為車籠埔斷層為平行層面斷層（bedding-parallel fault）；而濁水溪以南並非如此。

初鄉斷層位於車籠埔－大尖山斷層與雙冬斷層之間，呈東北-西南走向的活動斷層，位於濁水溪流域，了解初鄉斷層能更理解濁水溪南、北兩岸構造差異。過往研究對於初鄉斷層的幾何形貌有所爭議，前人認為在濁水溪有深度約 9 至10 公里的底滑脫面，但在幾何上難與車籠埔斷層連接。本研究蒐集前人地質及地球物理資料，參考前人的構造模型、集集地震同震GPS位移向量及地震資料，建立東西向的地質剖面，觀察初鄉斷層與相鄰構造的關係，了解地層在空間中的地層厚度變化以及區域構造的彼此關係。

根據本研究結果，初鄉斷層過往曾與大尖山斷層相連，做為調適大尖山斷層與車籠埔斷層間的幾何差異，與車籠埔斷層相連接於一底滑脫面，底滑脫面深度於濁水溪以南較濁水溪以北深，之間有側向的斷坡。

關鍵字：初鄉斷層、活動斷層、地震地質、平衡剖面

Joint Inversion of Seismic and Gravity Data to Explore the Structure of the Aseismic Zone in the Hsuehshan Range of Taiwan.

峻瑋 許

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Taiwan is located in the collision zone between the Eurasian plate and the Philippine Sea plate, leading to a significant number of earthquakes. These seismic activities serve as valuable materials for studying the orogeny. However, research on the Hsuehshan region is relatively scarce , prompting the utilization of available data to investigate the structure of Hsuehshan. This study employs long-term observational data from the Central Weather Administration and data obtained from the National Central University's temporary seismic station to explore the structure below the Hsuehshan region. Due to the limited resolution of seismic waves in shallow layers (<2 km), gravity data, known for its good control in shallow layers, is integrated. By combining gravity and velocity structure inversion, models of velocity and density for the research area are obtained. The seismic distribution within 15 kilometers offers good resolution only in shallow layers. Shallow Vp velocity maps show relative velocities that can be compared with Paleogene and Miocene strata on geological maps.The central Vp values in the research area exhibit relatively low values before a depth of 10 km, followed by a contrasting pattern with high-speed regions beyond 10 km depth.

台南盆地之演化分析

簡至暐[1]、涂嘉勝[1]、李通藝[2]、洪作緒[1]、高經富[1]、許庭瑄[1]、賴美澄[1]
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摘　要

位於台灣西南海域的台南盆地在傳統或非傳統油氣資源上都被認為是前景可期的區域，也是近年台灣周邊地區深水探勘的主要目標。此區域跨越主動式與被動式邊緣，有著複雜的地形轉折與大地構造地質背景。本研究涵蓋台南盆地的淺水區（陸棚區）與深水區（陸坡至盆底區，以及高屏斜坡區），依據區域性的二維與三維震測剖面之構造解釋結果，以構造恢復方法所揭示之構造演化史，綜合井下資料解析所得之大地構造層序，微體古生物分析所得之沉積環境演化，以及碎屑性鋯石分析所得之沉積物源等結果，修訂台南盆地之大地構造地層表，並繪製包含早白堊世、始新世、晚漸新世、早中新世、晚中新世、上新世與更新世末期共7張台南盆地演化立體圖，以呈現各個演化階段的盆地樣貌與特徵、沉積環境變遷與構造運動演化，以供後續該區域與周邊區域之石油系統評估、盆地模擬及其他相關地質研究作為參考。

關鍵字：台南盆地、大地構造地層、盆地演化

應用無人機攝影測量建構數值地形模型並解析大里地區海蝕平台的構造特徵

Applying UAV photogrammetry-based digital terrain model to investigate geological structures in Da-Li area, Yilan.

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隨著全台光達產製數值地形模型（DEM）的建置，使研究者可以克服交通、植被的限制，透過 DEM 判釋、描繪高精度的構造線等特徵。大里地區為雪山山脈東北翼的輕度變質帶，鄰近鐵路、北橫公路的交通路廊。區域構造上存在坊腳、石槽等數條斷層通過，且前人觀察到許多正斷層形成的斷塊，地質狀況較為複雜，因此本研究的目的在於繪製大里地區高精度構造特徵的分布。光達產製 DEM 的優勢在於排除植被的影響，測量過程可以不受交通的限制，並直接觀察區域地質特徵。然而該方法仍有部分限制，例如需要野外確認構造線的分類以及辨別地層岩性，因此我們使用無人機攝影測量方法補足這方面的需求。前人已透過高精度 DEM 繪製五萬分之一頭城圖幅地質圖，並推測宜蘭大金面山一帶有斷層系統的存在，不過尚需更多其他構造地質的證據支持。本研究透過 GIS 軟體分析數值地形資料，觀察並繪製大里地區構造線與地形特徵的分佈，透過迴歸平面法計算地層位態，獲取構造的幾何訊息，並到野外調查核實驗室的繪製結果。我們將測量結果呈現於區域地質圖中，並透過赤平投影工具，彙整區域構造的幾何特徵。本研究觀察發現地層大致為東北-西南走向的平緩褶皺，由海蝕平台北側至南側，傾角由東北向漸變至朝北傾斜，並在軸部地區存在破裂帶的分布。此區域兩組主要節理組，其中一組與海蝕平台的平移斷層走向相似，另一組則沿著東北-西南主要構造線分布，且前者節裡發育較後者發達。由赤平投影分析驗證海蝕平台的壓縮方向為西北-東南向，並嘗試與前人的應力研究互相比較。

石榴子石微量元素分析方法：使用雷射剝蝕感應耦合電漿質譜術

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摘　要

雷射剝蝕感應耦合電漿質譜術 (laser-ablation-inductively coupled plasma-mass spectrometry) 是原位 (*in situ*) 分析技術的一種。其具備分析快速、樣品製備步驟簡單、可分析元素範圍廣泛等優點，且主要用於量測礦物數十微米 (μm) 空間尺度下的微量元素濃度和同位素比值。將所得到的原位礦物化學資料結合地質年代與岩象觀察，即可進一步瞭解樣品的岩石成因。

使用雷射剝蝕感應耦合電漿質譜術時，須要針對不同礦物種類、基質和待測元素，調整雷射剝蝕系統和感應耦合電漿質譜儀的參數，以得到最佳化的結果。本研究使用中央研究院地球科學研究所之Photon Machines Analyte G2 193 nm 雷射剝蝕系統與Agilent 7900 四極桿 (quadrupole) 感應耦合電漿質譜儀，並鎖定存在於三大岩類中的石榴子石為研究對象，建立一個適用於石榴子石樣品的微量元素分析方法。石榴子石具有化學組成多樣和輕稀土元素虧損的特色，因此其分析難度較高。同時，欲分析之臺灣石榴子石顆粒大小可能僅50 μm，又含有分析時應避開的包裹體，也為分析方法帶來限制。

初步岩象結果顯示石榴子石中的礦物包裹體包含綠簾石、石英、鈉長石，可透過鈾、釷、矽、鈉、鈰、鍶、鋇等元素來監測訊號是否被混染，並有效避開包裹體的訊號區間。考量石榴子石的顆粒大小限制和主量元素組成，預設之雷射光束大小為40 μm，並使用矽為內標元素、NIST SRM 610為外部標準品。分析方法之單筆數據量測時間設定為大約一秒，最後以GLITTER軟體計算與校正數據。當使用雷射重複頻率 (repetition rate) 6 Hz、雷射能量密度 (fluence) 3.78 J/cm^{2}時，輕稀土元素中鑭 (La) 和鈰 (Ce) 的偵測極限約為 5 ppb，重稀土元素中鐿 (Yb) 和鎦 (Lu) 的偵測極限則分別是107 ppb和29 ppb。

本研究建立的石榴子石微量元素分析方法，未來將優先應用於臺灣石榴子石，探討其相關岩石成因。另外，此分析方法也可運用於量測同樣具有輕稀土元素虧損特性的鋯石，並能奠定石榴子石未來使用雷射剝蝕感應耦合電漿質譜術進行鈾-鉛和鎦-鉿定年的基礎。

關鍵字：雷射剝蝕感應耦合電漿質譜術、石榴子石、微量元素分析

以岩象影像分析及地球化學探討安山岩的礦物相特徵之研究

Application petrography image analyze and geochemistry on mineral assemblages of andesite

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摘要

大屯火山群是一座活火山，這座火山在經年累月的東北季風影響之下，火山地形型態仍保持完整，但是，部分區域在火山噴氣的影響之下，安山岩已轉變為各式各樣的蝕變礦物。由於，大屯火山群常見安山岩受到風化作用及熱液蝕變作用後的兩種產狀，一為類洋蔥狀/環狀紋路，另一為海棉孔洞狀。綜合野外現象和前人研究結果顯示，尚未有文獻探討安山岩在受到風化作用及熱液蝕變作用下，不同安山岩產狀的岩象影像量化與礦物種類之間的關係。因此，本研究以紗帽山、十八份熔岩、龍鳳谷、燒庚寮、天母古道及馬祖窟的安山岩為研究對象。首先觀察安山岩的岩象，再者，以影像分析軟體量化安山岩的礦物百分比；另外，以 X 光繞射分析安山岩的蝕變礦物及黏土礦物；接著，以 X 光螢光(ED-XRF)分析安山岩的地球化學百分比；最後，綜合這些結果說明類洋蔥狀/環狀紋路及海棉孔洞狀安山岩的形成過程及礦物相特徵。

關鍵字：岩象學、地球化學、安山岩

Keywords: petrography, geochemistry, andesite

臺灣東部地區水文地球化學與岩石礦物組成分布特性之研究

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摘　要

臺灣東部因陡峭嶙峋之地形特徵及地質複雜特性等內部因子，與全球變遷效應所引發的極端氣候變化之外部因子，造成不易採集代表性結晶岩類之樣本進行礦物分析與取得乾溼季代表性之水體，故長期缺乏岩石礦物組成及水文地球化學特性之相關數據。有鑒於此，本研究利用既有鑽井岩心及蒐集地下水與鄰近河川之地表水，進行岩石礦物及水文地球化學分析，可瞭解東部結晶岩之基礎地球化學資料及礦物成分，將可應用於地球化學模式建置、污染物運移特性評估與核廢料處置等相關領域。

本研究以本島結晶岩為主體，進行岩心樣本岩象學及礦物組成分析，並採集既有鑽探井之地下水及周圍地表水，瞭解水體地球化學特性。水體觀測項目包含多點位及深度之地下水與地表水流域基本化學參數(溫度、pH、導電度、總溶解固體、氧化還原電位、溶氧)、化學組成以及同位素資料。薄片分析及礦物主要元素組成分析結果顯示，本區以片麻岩夾層狀結構為主，裂隙礦物含長石、石英及層狀矽酸鹽類(主要為黑雲母)等。地下水pH值介於 7.0 至 8.5；總溶解固體介於100至 350 ppm；Piper圖分析結果顯示地下水及地表水屬$Ca\text{-}HCO_3$型態，地下水中主要元素濃度近似區域地表水；由氫氧同位素結果推估水體來源為天水。本研究將藉由不同季度之採樣數據，進一步探討結晶岩地區地球化學之時空分布特性，並透過穩定同位素資料，作為地下水補注模式及優勢地下水流向之佐證；後續將結合岩石裂隙礦物組成，探討深層可能之岩-水反應，提供未來深層地球化學演化之參考。

利用氣體 C_1 至 C_3 成份評估天然氣成熟度

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臺灣石油探勘礦區多屬氣田，其天然氣來源是值得探討、追蹤地球化學資訊，尤其地層下天然氣可能源自油母質直接裂解或產自原油大分子的裂解。長期以來希藉天然氣中甲烷、乙烷及丙烷等氣體成份協助、辨識地球化學訊息，以協助現場油氣探勘。

本研究以 A、B、C 三個礦區樣本進行分析，其中 A 礦區 125 個樣本、B 礦區 155 個樣本、C 礦區 159 個樣本之天然氣，發展以 $\ln(C_1/C_2)$與 $\ln(C_2/C_3)$關係辨識成熟度高低趨勢，同時也推估天然氣成熟度值。分析氣體中甲烷、乙烷及丙烷成份比例，利用 $\ln(C_1/C_2)$與 $\ln(C_2/C_3)$關係圖，可得知三個礦區天然氣成熟度趨勢，分別為 A 礦區> B 礦區> C 礦區，並推估：A 礦區天然氣成熟度約為 1.6%Ro-1.8%Ro；B 礦區天然氣成熟度約為 1.5%Ro-1.7%Ro；C 礦區天然氣成熟度約為 1.4%Ro-1.55%Ro，透過天然氣評估皆顯示 A、B 及 C 礦區的成熟度皆屬成熟以上，而此結果亦與凝結油輕成分參數(Heptane value)所推估之成熟度結果一致，顯示此法之可應用性。

Examining Holocene Climatic Shifts in Northern Africa, Tunisia: A Detailed Analysis of a Stalagmite Record from 10-2 thousand years ago

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Holocene climatic variations, notably in historically significant regions like the Mediterranean and North African areas, provide an avenue to explore the long-term impact of climate changes in the North Atlantic territory and the global linkage. Holocene $\delta^{13}C$ and $\delta^{18}O$ data of a stalagmite in La Mine Cave (36.03 1N, 9.68 1E, 975 m asl), Tunisia, enables examination of climatic shifts during 10.069 ± 0.051 to 2.129 ± 0.029 ka (relative to 1950 CE), offering insight into contrasting Mediterranean precipitation and North African Monsoonal influences in this region across decadal-to-millennial time scales.

Stalagmite $\delta^{13}C$ and $\delta^{18}O$ measurements were conducted through an online, automated carbonate preparation system, GasBench II, linked to an isotope ratio mass spectrometer (IRMS). An age model was determined using absolute U-Th dates, conducted using a multiple-collector inductively coupled plasma mass spectrometer (MC-ICPMS), Thermo Electron NEPTUNE. $\delta^{13}C$ values range between -4 and -8 ‰ during roughly 10-5 ka, transitioning to notably more negative values ranging from -8 to -10‰ within the 5-2 ka. Conversely, the $\delta^{18}O$ record displays a distinct positive phase (-5.5 to -5.0‰), succeeded by a sharp decline and a subsequent negative phase from 10-6 ka (-6.0 to -7.4‰), before trending back towards positive values of (-7.0 to -6.4‰), from 6-4 ka.

When comparing our Tunisian speleothem record with Northern Morocco, strong similarities in $\delta^{18}O$ exist from 10-6ka, likely due to comparable NAO-like influences. However, distinctions arise from approx. 6-3 ka. Initially wetter

conditions (6-4.9 ka) are followed by decreased precipitation (4.9-3 ka), indicating climatic fluctuations within the central Mediterranean region influenced by factors besides the NAO alone. Whereas $\delta^{13}C$ isotope value might be indicating a shift in C4 and C3 vegetation.

The origin of Proterozoic giant radiating dyke swarm systems on southern Superior Province, Canada

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Large igneous provinces (LIP) represent anomalous magmatism located far from plate boundaries. LIPs are mostly composed of mafic igneous rocks with subordinate intermediate to silicic rocks and cover extensive (10^5 km^2) areas of continental and oceanic crust. Their emplacement records the transfer of mantle materials to the crust. Precambrian giant radiating dyke swarms are thought to represent the plumbing system of eroded ancient LIP. Moreover, mafic dyke swarms can help to reconstruct ancient supercontinents, identify distinct mantle sources, and locate mineral deposits. The Superior Province of the Canadian Shield preserves one of the highest mafic dyke densities amongst all Archean cratons. Eight dykes/sills swarms from southern Superior Province are selected for this study. They include Matachewan (2.5 Ga), Fort Frances (2.2 Ga), Marathon (2.12 Ga), Biscotasing (2.16 Ga), Nipissing (2.2 Ga), Sudbury (1.2 Ga), Abitibi (1.1 Ga), and Keweenawan (1.1 Ga). New geochemical criteria (Th/Nb versus TiO_2/Yb) has been proposed for fingerprinting the mantle sources of LIPs and mafic dyke swarms. The application of this new method indicates that the Matachewan swarms and Nipissing sills are derived from a subduction-modified lithospheric mantle (SZLM). The Biscotasing and Marathon swarms are derived from a source transition between MORB and OIB. The Fort Frances swarm is derived from the MORB domain. In comparison, the younger dyke swarms are related to an OIB source with the exception of the Keweenawan, which shows a trend from transitional to SZLM source. These results indicate that the southern Superior Province underwent several magmatic events during the Proterozoic, possibly associated with the supercontinent cycle. These magmatic events were derived from distinct mantle sources beneath the Superior Province.

Keyword: Proterozoic, Superior craton, Large igneous province, Giant radiating dyke swarm

Spatial and Temporal Variations in the Solomon Magmatic Arc from Eocene with Implications for Subduction Polarity Reversal

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Abstract

SW Pacific marks an excellent example for studying SPR but its nature, origin and timing remain unclear due to limited studies of good quality. Here we report the first robust set of Zircon U-Pb ages and Hf isotopes, and whole-rock geochemical and isotopic data of igneous rocks sampled from Choiseul and New Georgia Group (NGG) islands. Choiseul amphibolite, dated back to 46.5 ±1.2 Ma is geochemically and isotopically similar to other mafic rock-types on island. These rocks are low-K tholeiites with Pacific mantle signature on εNd(t) vs εHf(t) space suggesting the initiation of southward subduction of the Pacific plate and their origin in an oceanic arc-backarc setting. After a magmatic hiatus of ~12-10 m.y., Ghizo low-K calc-alkaline Tonalites dated at ~34 Ma indicate first arc magmatism in NGG with flat to variably enriched LREE over HREE. And later, medium-K (an andesite dated at 19.3±0.7 Ma; diorite dated at 18.3±0.7 and 11.6±1.6 Ma) to high-K calc-alkaline magmatism lasted in NGG till the Quaternary, as evidenced by the ~2Ma granodiorite and ~0.7Ma andesites in NGG and Choiseul, respectively. These rocks from the Late Eocene to Quaternary exhibit an Indian mantle signature on εNd(t) vs εHf(t) space. However, Miocene to Recent, calc-alkaline rocks show a limited range in ISr (0.7038 -0.7043) and positive values of εNd(t) [+6.2 to +5.8] and εHf(t) [+11.3 to +10.4], suggesting a magma source that is isotopically less depleted than the Eocene rocks [εNd(t) of +8; εHf(t) from +14 to +12] and latest SPR. Such a secular change is also consistent with the compositional variation observed from the ~46 Ma arc tholeiite to the low-K and then high-K calc-alkaline magmatism in SIA, which we attribute to enrichment in the magma source region because of the involvement of micro-continental fragments in the region. Future work on Pb isotope would be a valuable tracer to discriminate between mantle components and to understand the temporal evolution of mantle hetrogeneities.

Keywords: Solomon Island Arc, subduction polarity reversal, zircon U-Pb age, Sr-Nd-Hf isotope.

Student Poster Competition

(1) University/Advisor: IES, Academia Sinica and NCU/ Prof. Chung, Sun-Lin
(2) Degree/Grade: 4th Grade (PhD.)
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台灣西部不同地質條件之集水區誘發崩塌的降雨條件分析

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摘　　要

降雨是引發崩塌災害的主要因素之一。台灣地形特徵複雜、地勢陡峭、並位處於亞熱帶氣候帶，氣候多變且降雨充沛，加上人為過度開發等因素的綜合影響，導致崩塌災害事件頻繁發生。為減輕崩塌造成的影響，掌握各集水區誘發崩塌的降雨條件，進而提高預警效果，將成為關鍵之議題。

為確定台灣不同地區的降雨條件對崩塌程度的影響差異，本研究選擇了台灣西部由北至南的五個主要集水區作為研究區域，包括石門水庫集水區、大甲溪集水區、濁水溪集水區、曾文溪集水區、以及高屏溪集水區。另外，選取了自 2004 年至 2019 年間具代表性的 10 場中度以上之颱風事件作為研究對象，進行降雨條件的分析並建立其與崩塌特性之間的關係。此外，從分析結果更進一步探討了各集水區之不同地質特徵對誘發崩塌所需之降雨條件的影響。

結果顯示，在石門水庫集水區、濁水溪集水區、及高屏溪集水區，颱風期間的累積降雨量為主要控制該集水區崩塌特性的降雨參數。當颱風期間的累積降雨量愈高時，該集水區將會有更大規模的崩塌發生。另一方面，在大甲溪集水區及曾文溪集水區，崩塌特性則是與颱風期間的尖峰降雨強度有較高的相關性。

本研究透過了解各集水區控制崩塌特性的不同降雨條件，有助於在災害預警中更加因地制宜，也能在災害來臨時更迅速地應對，做出更有效的判斷，以最大程度地保障人民的生命財產安全。

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Slope geological model and topographic evolution of paleo rockslide — southern section of dip slope area along the right bank of Chishan River, Kaohsiung City

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Abstract

Taiwan island is an area with high uplift and erosion rates area with frequent geological tectonic activities and high annual precipitation. The widespread and thick, young or old colluviums could be found in the mountainous area. It implies that landslide is a common process in Taiwan island since long-term ago. The potential large-scale landslide areas usually consist of colluvium with regolith and rock mass. Moreover, there are many platform terrains of different sizes on the dip slope along the right bank of Chishan River was found in previous study. Also, the Jiasian cases were inferred as the deposits of paleo-rockslides (displaced rock mass, DRM) based on the established slope geological model. However, most platforms were identified by topographic analysis only without in-situ investigation. According to the preliminary topographic survey, this study chooses two large platforms in the southern section of the dip slope along the right bank of Chishan River. The areas of Mujiliao and Tianziding platforms are about 6 and 8.2 hectares, respectively. Moreover, the front part of Mujiliao platform occurred a deep-seated landslide during the 2016 Typhoon Megi. Therefore, this study aims to establish the slope geologic model and attempts to present the topographic evolution of Mujiliao platform. Based on the field investigation, the sedimentary rock members and their boundaries of study area are mapped for geologic map and profile. Besides, the multi-period images and topographic change could be adopted for the slope geologic model. The platforms are mainly composed of interbedded layer with a gentle dip angle (5°-20°) of bedding (DRM), which is significant gentler than the bedrock (dip of 40°). Finally, the slope geological models show three types of platform terrain. Mujiliao, Tianziding, and Chenwu (a small case) platforms show the active type with failure of DRM, stable type with slight gully erosion, and residual type with mature gully development, respectively.

Keywords: Slope geological model, topographic evolution, geological profile, paleo-rockslide, landslide

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超含水相B在高溫高壓下的熱傳導率及其對地球深部水循環的影響

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摘　要

地球表面覆蓋了大量的水，這些水可藉由板塊隱沒進入地球深部，影響了地球內部的物理及化學性質，是我們了解地球的動力學及熱演化的重要關鍵。緻密含水鎂矽酸鹽(dense hydrous magnesium silicates, DHMS)為隱沒板塊中隨著溫度與壓力變化相變而成的一系列含水礦物，可以含有水在其晶體結構中，對地球深部水循環有重要的影響。其中，超含水相B(Superhydrous Phase B)，被認為是能攜帶許多水並穩定存在於地函過渡帶至下部地函最上部的重要含水礦物，然而其性質對於隱沒板塊的影響仍有許多不了解處。

本研究將合成的超含水相B，置於高壓鑽石砧及電阻式加熱系統中模擬地球內部的高壓及高溫環境，並利用時域熱反射技術(TDTR)量測其熱傳導性質，記錄隨著溫度及壓力上升的熱導率變化，並與其他含水礦物、地函礦物進行比較。

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探討地核地函邊界物質之熱傳導率與其對地球熱演化歷史的影響

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摘　要

地核地函邊界物質之熱性質對於研究地球熱演化歷史至關重要，無論是研究地球冷卻過程或者是以電腦模擬地球內部動力學，其皆為重要參數。在地核地函邊界，有兩個地震學觀測到的地震波低速帶：大剪力波低速省（Large Low Shear Velocity Provinces）和超低速帶（Ultra Low Velocity Zones），其中超低速帶被認為和地函熱柱之生成相關。我們透過高溫高壓的礦物物理實驗，對超低速帶可能的礦物之一: 鐵方鎂石進行研究。以高壓鑽石砧結合加熱技術，模擬地球深部高溫高壓之環境，並使用基於超快雷射之時間域熱反射法量測其熱傳導率。實驗結果顯示鐵方鎂石的熱傳導率遠低於周邊地函物質之熱傳導率，以此我們可以推論地核向外釋放的熱有一部分將會累積在超低速帶處，從而使該區域之溫度升高，以利地函熱柱之生成。此實驗結果也和先前地震學觀測的結果一致，為未來地球深部實驗與電腦數值模擬提供重要的物理性質。

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臺灣地熱場地層儲存及流體流動特性
——以大屯火山群和東部板岩帶為例

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摘　要

再生能源一直是近年來備受關注的議題之一，而台灣位於太平洋火環帶上，地底下有豐富的地熱資源，在1970年代爆發第一次能源危機時，就曾對全台進行地熱探勘調查，但此後卻無明顯的進展，直到近年，政府機關才再次重啟調查。地熱能源要做到能夠發電必須滿足三個條件：足夠的熱源、水以及流體流動的管道，在岩體中，流動的管道指的主要是岩體的裂隙，比如節理面、葉理面等，重要參數為水力內寬，而力學內寬與孔隙率則為流體儲存特性之參數。

本研究使用 YOKO2 孔隙率/滲透率量測系統，對大屯火山群四磺子坪 E－303 號地熱探勘井所鑽出的五指山層的砂岩以及臺東縣延平鄉紅葉村紅葉層的板岩進行完整岩石樣本的孔隙率和滲透率之量測，以及含有節理的砂岩樣本和鋸切板岩進行水力內寬及力學內寬的量測。其中孔隙率和力學內寬是透過波以耳定律量測，滲透率和水力內寬則是以穩流法與壓力脈衝衰減法來量測。結果顯示，當有效正向應力在 2.7 ～ 30 MPa 時，砂岩的孔隙率為 3.8% ～ 4.8%，滲透率為 2.0×10^{-16} ～ 2.16×10^{-17} m^2；有效正向應力在 2.7～60 MPa 時，含有節理的砂岩樣本的水力內寬為 10.0 ～ 26.0 μm；力學內寬為 45.5 ～ 126.4 μm。當有效正向應力在 2.7 ～ 10 MPa 時，板岩的孔隙率為 0% ～ 5.2%，垂直與平行葉理方向板岩之滲透率為 5.7×10^{-19} ～ 2.3×10^{-20} m^2，大致上，板岩平行葉理方向之滲透率大於垂直葉理方向；當有效正向應力在2.7 ～ 30 MPa 時鋸切板岩的力學內寬為 19.4 ～ 235.3 μm，水力內寬為 2.7～4.8 μm。雖然在有效應力為 10 MPa 以下，鋸切板岩的力學內寬大於砂岩節理的力學內寬，但因鋸切板岩的水力內寬小於砂岩節理的水力內寬，其地熱發電的效能會比較差。綜觀上述，只考慮岩性，若要使用地熱發電，大屯火山群的發電效益會比臺東紅葉村高。

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Illuminating basement geometry and potential geothermal reservoirs in the Ilan plain, northern Taiwan through microtremor analysis with a new dense array

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ABSTRACT

The Ilan Plain in northern Taiwan, located at the southwestern tip of the Okinawa, is subject to back-arc extension potentially with magma intrusion and elevated geotherm. To explore its geothermal resources, a nested dense seismic array comprising 81 stations covering the entire Ilan Plain and 186 sensors positioned around the Hongchailin area was deployed from July 2022 to January 2023. In this study, the Horizontal-to-Vertical Spectral Ratio (HVSR) method is first employed to constrain the basement geometry of the Ilain Plain. We performed the Fourier transform for three-component data at each station, derived and smoothed H/V amplitude spectral ratio, and searched for the spectral peak. The peak represents a resonant frequency that corresponds to the thickness of alluvial deposits overlying the bedrock. The results show a good correlation with previous studies by seismic profiling and S-P conversion phase. With this construction of basin geometry as initial two-layer models, the degree-of-polarization method (DOP-E) will be used to further extract the Rayleigh wave ellipticity and invert for a detailed 1-D shear velocity model at each station. The developed procedure of microtremor analysis is anticipated to offer a non-invasive and seamless single-station approach for providing rapid assessment of basement and geothermal structure for rifted basins.

Keywords: Microtremor analysis, HVSR, Basin structure, Geothermal energy, Dense seismic array.

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利用三維熱–水–力耦合數值模式評估地熱案場抽注水管理方案：以清水地熱案場簡化模型為例

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摘　要

地熱發電是台灣再生能源發展中重要的項目之一，其中位於宜蘭縣大同鄉的清水地熱案場為發展最早且相當成功的案例，目前已進入商業運轉階段。然而，地熱發電效益取決於生產的熱水量。其可能因為抽注水的管理不當而引起冷鋒突破(cold-water front breakthrough)，進而降低發電效率，甚至導致地熱井之產能嚴重衰退而沒有經濟效益。因此本研究希望利用熱-水-力耦合(thermal-hydraulic-mechanical coupling)數值模擬方法，評估現有抽注水操作下的取水與岩體中水溫變化狀況，並嘗試以現有各井體資料，評估抽注水管理方案。

本研究首先蒐集前人針對清水地熱場址進行之地質調查與相關研究成果，並蒐集熱源、流量以及發電廠運作時採用的抽注水量等資料；以多物理場模擬軟體COMSOL Multiphysics，建立簡化的三維地質模型，並考慮地層內部熱傳、水流及固體變形之間的交互作用，建立熱-水-力耦合數值模式。研究中藉由軟體平台組建不同熱-水-力模組，透過調整各輸入變量進行模擬與分析，以建立適當的熱-水-力耦合模式，並取得合理的參數設定。並以此簡化模型為基礎，設計不同的抽注水情境，以觀察不同情境設定對產能之影響，用以提供清水地熱電廠抽注水管理之參考。本研究完成清水地熱場址簡化模型的熱-水-力抽注水模式建置與模擬工作，並進行參數敏感度分析，瞭解不同參數對熱-水-力耦合系統的影響。結果顯示，抽注水井流率對於模擬結果，相較其他參數有更高的敏感度。此外，在後續不同的抽注水情境模擬中觀察到，抽注流率與井體間距對熱-水-力耦合系統影響顯著。因此，對地熱電廠之抽注水量規劃與井體間距設計須特別注意。

關鍵詞：清水地熱案場、簡化地質模型、熱–水–力耦合數值模式、敏感度分析、抽注水模擬。

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結合異質性地質模型與水-熱數值模式探討台灣宜蘭礁溪溫泉水資源管理

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摘　　要

近年來，休閒活動在大眾生活中佔據越來越重要的地位，而溫泉區一直是人們冬季旅遊的熱門選擇之一。隨著永續觀念的興起，觀光發展需要同時考慮溫泉的永續利用。本研究透過整合異質場地質模型和地下水流數值模式，以評估台灣宜蘭地區著名的礁溪溫泉適當的溫泉使用量。本研究首先蒐集不同來源的地質鑽探資料，以及2020年間觀測井水位及水溫資料、河川水位和抽水量等水文觀測數據。接著，運用地下水模擬系統(Groundwater Modeling System, GMS)軟體，先以地質統計方法分析研究區水文地質材料的空間分布特性，再輸入T-PROGS套件，以馬可夫鏈法(Markov chain)產製數十個實現場的沉積層異質性水文地質模型，並將各個實現場與底部的均質性基盤整合為三維地質模型。因實務上無法針對每個地質模型進行數值模式率定，因此本研究提出一套篩選流程，選定一礁溪地區代表水文地質模型。隨後，再將其轉換為MODFLOW地下水流數值模型，並結合MT3DMS套件進行水-熱模擬，以獲取地下水流場和溫度場的分布情況。

研究結果顯示，水文地質材料在東北-西南方向上有最大連續性，與沉積粒徑分布一致。當三維地質模型建置數達30個時，整體地下水位的變異數及平均值趨於穩定。因此，本研究再針對此30個地質模型模擬的地下水位，以決定係數(R-squared)最高及平均絕對誤差(Mean absolute error)最小的統計特性，挑選模型21為代表地質模型。本研究成功整合了異質性沉積層和均質性基盤，並轉換為地下水流與溫度傳輸數值模型。地下水流模擬顯示，沉積層模擬水位與實際觀測水位相當一致($R^2 = 0.9$)，顯示地下水流模式具有一定的代表性。熱傳輸模擬結果顯示，礁溪地區溫度場的空間分布與目前溫度觀測相似。建立之模式在考量水量與水溫情況下，進一步評估了研究區域的合適抽水量，提供礁溪地區未來溫泉資源規劃之參考。本研究建立之研究流程與架構，可以作為不同溫泉地區水資源管理的依據，實現對溫泉資源的永續發展目標。

關鍵詞：台灣礁溪溫泉、水資源永續管理、異質性地質模型、馬可夫鏈法、地下水流模擬、溫度傳輸模擬。

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關子嶺與中崙地區地下構造剖面

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摘　要

為達到淨零碳排，我國將地熱視為重要、穩定且可靠的再生能源，且其不受天氣的限制，可以 24 小時持續運轉。本研究選擇岩層溫度達攝氏 150 度，並且有地表特徵之溫泉區—台南市關子嶺與嘉義縣中崙地區為研究區域。為了較有效的探勘地熱發電潛力區域，背斜軸部較老的地層可能具有較高溫的岩層，所以研究著重在中崙背斜與南寮背斜，並且著重岩層中孔隙率與滲透率良好的木山層與南莊層。與前人相比，本研究也注重於淺層區域裡的主要裂隙，例如：枕頭山斷層、六重溪斷層與凍子腳斷層等。我們調查與確認了構造與地層的相互先後截切順序，以及是否有與斷層共同發育之大規模裂隙，藉此找到地熱發電所需之水循環通道等。

本研究統整了台灣中油公司在此區的六處鑽井資料，輸入至 MOVE 軟體中製成三維地下模型後，再利用中油及地礦中心之地質圖幅和野外考察鄰近剖面的地層位態與斷層投影至西北-東南向的剖面上，形成地質剖面圖的基礎架構。本研究用轉折法（Kink Method）來重建出地底下的構造幾何形貌，建置出橫跨嘉義縣中崙地區的一條地質剖面（AA’），與橫跨台南市關子嶺地區的兩條地質剖面（BB’和 CC’）。藉此方法能使劃分傾角區域（Dip Domain）和繪製地層時可以較清晰、有系統地展示地質剖面的軸線和斷層的位置。

中崙 AA’剖面中有向西傾 84 度且斷距 300 公尺的凍子腳斷層；關子嶺 BB’剖面中有向西傾 81 度之枕頭山斷層，與地物與地化指出富集地下水的深度吻合；CC’剖面中發現向東傾 70 度六重溪斷層，以上沿褶皺軸部發育的斷層推測為關子嶺與中崙地區的重要水通道。本研究提供淺層裂隙系統新的解釋，對於地熱開發能給予重要的基本資訊。

以TOUGH2數值方法檢驗宜蘭平原南部裂隙主控型地熱概念模型

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摘　要

本研究旨在評估深層地熱在宜蘭平原的潛力，並進一步建立三星至紅柴林區域地熱概念模型。目前綠能意識抬頭，地熱能源的開發技術日漸增強，宜蘭平原位處沖繩海槽張裂末端，周遭地區如龜山島岩漿活動、清水和土場等宜蘭周圍山區之溫泉露頭皆暗示宜蘭地區極具地熱發展潛力。目前對於宜蘭平原沖積層下之區域構造已存在初步概念模型，並有紅柴林三口一千米以上之深井井測資料，但模型仍缺乏深部地下水流及熱傳輸數值模式的驗證。基於前述，本研究利用GIS軟體彙整過去在三星周圍地區之地質資料、地球物理探勘及現地井溫資料，並搭配Python設置岩石及破碎帶之熱傳和水力參數，建置宜蘭裂隙主控的地熱概念數值模型。使用數值模擬套件TOUGH2 (Transport Of Unsaturated Groundwater and Heat)計算在模型所設置之熱流和導水裂隙情景下，驗證當前地熱概念模型以及解釋紅柴林多口井中所量測到之溫度分布。

對比前人探勘成果，中央山脈盧山層逆衝於雪山山脈之乾溝層、四稜砂岩等地層之上，多數地層和褶皺走向為東西向。在蘭陽溪周圍存在傾向海槽中心之高傾角正斷層，同時震測剖面和地電阻的結果，顯示三星至紅柴林區域可能存在多條南北向潛在走向滑移構造。

依地下水流及熱傳輸數值之結果，本研究認為宜蘭平原西南部區域的四稜砂岩受斷層截穿後，岩層破碎具有較高之滲透率；同時紅柴林一號井東側南北向之低電阻構造可能為本區域主要之熱流來源，熱液進入破碎的四稜砂岩中後與較冷之地下水混和，造成紅柴林二號井和耕莘井中地溫停滯，而混和後向東遷移之地下水造成宜蘭平原東南區域淺層普遍具有較高之地溫梯度。

關鍵字： 宜蘭平原南部地熱區、地熱概念模型、裂隙儲集層模擬、TOUGH2數值模擬、地溫梯度

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3D Velocity Structure and Geothermal Anomalies Inferred from Noise Phase Cross-Correlation in Ilan Plain

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ABSTRACT

To investigate the seismic characteristics of Ilan Plain, the ILAN2014 experiment deployed 163 temporary stations from August 14, 2014, to January 14, 2015, spaced between 1 to 4 km across the entire area. Our study focuses on seismic ambient noise analysis, which predominantly attributed from primary and secondary microseisms. We calculate the empirical Green's functions (EGFs) of the station pairs by Phase Cross Correlation (PCC) technique. PCC relies on the instantaneous phase information of coherent signals which means, it is sensitive to waveform phase similarity but less sensitive to strong amplitude features (amplitude unbiased). Furthermore, we stacked by time-scale Phase Weighted Stacking (ts-PWS) strategy for signal enhancement and perform the dispersion analysis on group velocity. The group velocity distribution maps reveals the low velocity along the coastline while the mountain side has higher velocity. Ultimately, we use the picked dispersion curve data information to perform the inversion. To invert shear wave velocity structure, the wavelet-based sparsity-constrained method by Fang et al. (2015) were employed. Three different initial model including 1D linearly increased velocity model, average 1D velocity from Huang (2003) and combined velocity of Huang (2003) and Su et al. (2019) were used to reach consitent convergence result. The third approaches provide useful suggestions on the estimated Vs distribution structure features can reach ~2.5 km. The inversion revealed extremely low Vs (Vs < 1.0 km/s) imbedded in the high Vs velocity background at various depths in the south-western part of Ilan Plain that consistent with the known geothermal anomaly sites. Although some station may not provide enough depth solution, however detectable geothermal anomalies are very positive and show fairly distinct features. The exact location and its interpretations may require more careful study and verification.

Keywords: Ambient Noise, Phase Cross Correlation, Phase-weighted Stack, Dispersion Analysis, Surface-wave Inversion, Near-surface Velocity Structure

以同位素地球化學方法評估台灣中崙及關子嶺地熱區潛在熱水儲集層及其溫度

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摘　要

地熱是一種相對穩定且乾淨的再生能源。地熱流體的溫度、儲集層深度及所含之化學物質是否適合作為地熱能源使用，即為需要進行評估的事項，否則在開發後會存在各種隱憂。本研究鎖定同為地熱潛勢區的台南關子嶺以及嘉義中崙地區為研究區域，透過乾濕季節的時間序列採樣，進行此兩地區11個樣點的水化學元素及同位素分析，另配合鑽井岩心樣本進行比對討論，以探討地下熱水的潛在儲集層及水溫。本研究透過現地水化學參數觀測（包含pH、氧化還原電位、溶氧、導電度等）及氫氧同位素資料，了解在乾、濕季節的情況下，天水或地表水如何影響及補助溫泉水源。根據採集水樣之氫氧同位素及Cl濃度數據，中崙及關子嶺溫泉水主要由天水、孔隙水、黏土礦物脫水三者所控制，其相對比例平均為46.8%、17.5%、36.2%。關子嶺與中崙地下熱水的主要水源是來自於黏土礦物脫水或水岩反應為主，其次是海水孔隙水源。而經由地表裂隙下滲的天水與地下熱水混合會進一步影響溫泉水的平衡，在中崙地區濕季的表現相對明顯，關子嶺地區對於此一現象則較不明顯；此現象主要與中崙地區凍子腳斷層所主導的裂隙，容易使得天水或地表水下滲與熱水混染有關。欲確定水岩反應是否達到平衡，應取天水控制比例愈低之溫泉水作為指示水岩反應平衡之水樣，因此乾季的溫泉水及關子嶺地區溫泉水較傾向為已達平衡之地熱水源。本研究根據臺灣中油公司關子嶺與中崙岩心岩相與地表地熱流體的鍶同位素特徵比對，指出在關子嶺岩心深度約2.9公里處、中崙地區約1.4公里處為可能的熱水儲集層。本研究進一步以SiO2及Na-K地質溫度計雙重指標進行熱水溫度的評估：關子嶺熱水水溫約為155°C；中崙地區則為125～150°C之間。根據中崙及關子嶺地區熱水溫度及儲集層的深度，符合沉積岩型地熱具有開發價值的潛力（根據Moore & Allis, 2016）。結合地球化學及其他地球物理的探測資料，將有助於選址及開發，為台灣地熱發電的潛力場址。

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臺灣西部紅樹林區域沉積物有機碳含量研究與其控制因素之探討

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摘要

在當今全球面臨氣候變遷的影響下，人們開始關注如何有效減少大氣中的碳排放。紅樹林藉由光合作用與潮汐作用造就了分解速率低的厭氧沉積環境，使得有機碳不易分解並具有較長久的固碳效果。紅樹林地下部沉積物的碳儲存能力高，因此紅樹林的碳匯能力在減緩全球暖化速度與調節氣候上具重要潛力。本研究旨在量化臺灣西部紅樹林區域沉積物有機碳含量並推測控制因素。

本研究於關渡自然公園，挖子尾自然保留區，新豐濕地以及四草大橋鹽水溪作為探勘地點，並在樣區設立紅樹林與砂質海灘樣點採 50 到 100 公分的淺層岩芯。利用元素分析儀將紅樹林區域與砂質海灘之 TOC（total organic carbon）含量做對比佐證紅樹林的碳匯能力，並用於計算平均每單位面積的碳，並利用雷射粒徑分析儀分析沉積物粒徑組成。

四草大橋鹽水溪紅樹林的 TOC 含量為 0.8%-0.9%， 沙洲 TOC 含量為 0.5%。挖子尾 TOC 含量為 0.6%-1.6%之間，砂質海灘 TOC 含量為 0.4%。得出紅樹林比沙洲 TOC 含量高。推測濕地吸收大氣中的二氧化碳並儲存在紅樹林底層分解速率低的厭氧沉積層中，同時間 TOC 比較多的細顆粒在濕地累積，導致兩地 TOC 差異。砂質海灘 TOC 的含量少是因碳源為無機碳，主要來自砂灘區域的碳酸鈣生物碎屑。

此研究亦通過岩芯樣本討論沉積物 TOC 在不同深度的變化以及可能的影響，以四草大橋鹽水溪與挖子尾自然保留區為例。四草大橋鹽水溪紅樹林岩芯

TOC 從 1.6%下降到 0.6%，顯示隨深度增加 TOC 下降。紅樹林區域細顆粒比與 LOC（labile organic carbon）/TOC 有關，深度越深細顆粒的比例越低，而沙洲的細顆粒比沒有太大變化。說明研究區域沉積環境粒徑較小的泥質沉積物可以儲存較多的 TOC，粗顆粒的砂質沉積物因總表面積較低不易吸附有機質。而挖子尾自然保留區紅樹林岩芯測定結果並沒有隨深度增加 TOC 下降，顯示沉積物 TOC 在不同深度的變化不能以單一地區的推斷整個臺灣紅樹林區域的結果。未來預計透過河口多樣性、潮汐、季節、波浪作用、紅樹林種類和懸浮顆粒等等的因素來找出不同深度 TOC 變化的原因。

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考慮異質性膨潤土內氣體遷移之多相流與黏彈性力學耦合數值模擬

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摘要

高階放射性廢棄物最終處置方式為深層地質處置，以多重障壁概念，將廢棄物包覆在處置罐中，並運至地層至少三百公尺以下的岩體中，再填滿緩衝材料，藉由隔離、遲滯原理以確保廢棄物衰變到無害程度，與生物圈隔離，保護民眾健康及環境安全。然而，經處置數百年後，廢棄物自身衰變產生熱，處置系統溫度隨之上升，熱膨脹使應力改變，進而造成水力及化學效應產生。在低氧環境下金屬容器腐蝕、廢棄物自身放射衰變、水輻射分解均可能產生氣體，隨著氣體持續累積，一旦作用在緩衝材料上的應力無法承受氣體壓力，孔隙將逐漸擴張並產生裂隙，氣體藉此流出至岩體，影響處置系統之能力，造成安全性的危險。因此，緩衝材料在系統中扮演著極為關鍵的角色，膨潤土為常見的緩衝材料選擇，在實際情況下，膨潤土含有不同的顆粒排列、孔隙率和滲透率，呈現異質性的空間分布，這種異質性可能在高孔隙率及疏鬆顆粒排列之區域，形成優先通道，使氣體更容易流通，進而影響氣體的遷移行為。因此，本研究先以膨潤土的均質性空間分布利用 THMC 數值模式模擬，結果成功地顯示氣體壓力累積和突破之變化，並進一步考慮異質性改變孔隙率及滲透率等材料參數，分析異質性所形成的優先通道對氣體遷移之影響，也將針對耦合行為做說明。

關鍵字： 高階放射性廢棄物、深層地質處置、緩衝材料、膨潤土、異質性、氣體遷移、耦合數值模擬、多相流、黏彈性力學

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Examining the coseismic deformation in Taiwan through the Empirical Orthogonal Function (EOF) analysis on continuous GPS data

Min Lee, B. F. Chao, Ray Y. Chuang

Abstract

The extensive nationwide Global Navigation Satellite System (GNSS) network serves as a valuable tool for accurately monitoring three-dimensional coseismic crustal deformation. During earthquakes, certain GNSS stations, situated at considerable distances from fault traces, have exhibited permanent deformation, which prompts an investigation into the spatial patterns of permanent deformation induced by active faults. Conventionally, extracting coseismic signals from GNSS involves utilizing the least-squares estimates derived from individual station time series.

EOF, or Empirical Orthogonal Function analysis, possesses the capability to flexibly unveil the concealed and prevailing patterns within a dataset. The EOF analysis effectively captures coseismic deformation through coherent spatial patterns and temporal evolution. It could also isolate and address the prevalent common-mode errors present in GNSS data as distinctive and separate EOF modes. In this study, we apply EOF analysis to examine the spatial patterns and time series for recent major earthquakes in Taiwan, providing evidence of the geological structures related to the active Taiwan collision.

Keywords: Empirical Orthogonal Function, coseismic deformation, continuous GPS

由InSAR時間序列探討2017－2021黃石火山之地表變形

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摘　要

黃石火山位於美國懷俄明州西北部地區，為全球超級火山之一，其主要形成機制為地函熱柱與北美大陸板塊相互作用，過去曾發生過三次大規模噴發，分別為 210 萬年前、130 萬年前及 64 萬年前，最後一次噴發活動所形成的破火山口(caldera)則位於今日黃石公園內。黃石火山作為北美地區火山、熱液和地震活動頻繁的區域，以及它在噴發後對於北美地區的居民和全球氣候變化的影響，需要進行長期監測，其中一項即為用以觀測地表變形的大地測量：從 1923 年開始的精密水準，到 1985 起的 GPS 及 1992 年的第一幅 InSAR 資料，至今已記錄了一系列黃石火山的地表抬升與下降事件。其中引發眾人關注的事件是 2004 年至 2010 年這段期間，GPS 及 InSAR 皆觀測到了黃石破火山口的兩個再生穹丘(resurgent dome) Sour Creek 和 Mallard Lake 有快速隆起的現象，每年快速抬升約 7 公分。相反的在破火山口邊緣外的 Norris 地區間歇泉盆地則呈現地表下降趨勢，每年大約下降 3 公分。前人研究將這段時間的地表變形原因歸因於破火山口底下的淺部岩漿室膨脹，並導致熱液流體重新分布的結果。其後 GPS 又持續記錄了破火山口的快速地表變形，包括 2010~2014 的下沉、2014~2016 的上升、以及 2016~2021 的再次下沉，但這幾次事件都缺乏 InSAR 觀測的佐證。因此本研究應用 2017~2021 的 Sentinel-1 衛星影像進行差分干涉以及時間序列分析，期能提供此時期黃石火山地表快速下降事件的空間解析。初步的研究結果顯示，2017~2019 Norris 盆地與 Mallard Lake 北方區域為抬升，兩個再生穹丘為下沉，2019~2021 有別於以往兩個再生穹丘與 Norris 盆地的反向地表變形，這三個區域皆顯示地表下降，且 Mallard Lake 北方區域有持續抬升情況。此重要發現或許對於黃石火山底下的熱液構造及活動可提供新的認知及解釋。

關鍵字：黃石火山、地表變形、Sentinel-1、差分干涉、時間序列分析

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利用GPS資料分析縱谷中段震間變形

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摘　要

菲律賓海板塊每年以約8公分速度向西北方的歐亞板塊移動，造成位於臺灣東部的縱谷有著極為活躍的構造活動。雖然透過地表地質調查、大地變形以及地震定位等研究方式，我們對位於縱谷東側的縱谷斷層其活動特性已有相當程度的了解，但對於位在縱谷西側的中央山脈斷層系統來說，我們對於其運動速率、斷層鎖定率等特性仍所知有限。為瞭解中央山脈斷層系統於過去數十年間內於震間期的活動特性，以及其在此期間斷層鎖定區域的分布，本研究利用中央研究院佈設於縱谷中段區域的GPS連續與移動站觀測結果，求得各站點於震間期的移動速率，分析縱谷中段區域於2022年關山—池上地震以前的震間期速度場，並結合目前震後地表破裂調查成果與已知的斷層模型後，利用彈性半空間模型推算中央山脈斷層系統於縱谷中段於2022年以前的震間期活動特性，以瞭解該斷層在震間期時斷層鎖定區域的分布，以及中央山脈斷層系統與鄰近斷層活動的關聯特性。本研究的初步結果發現中央山脈斷層中段淺部在2022年關山—池上地震前30年間處於明顯的閉鎖狀態，閉鎖區間與2022年地震的破裂區間約略相符，與其東側的縱谷斷層活動特性有明顯的差異。其閉鎖深度因GPS測站分布限制而難以精確控制，但與2022地震破裂帶深度應可相互映證。此一結果顯示中央山脈斷層系統為縱谷中極為重要的活動與孕震構造，建議須對其上盤區域進行長期的大地變形監測。

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Detecting interseismic deformation in Southwestern Taiwan by using InSAR and GNSS time series

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Abstract

Surface deformation during the interseismic period is the key for understanding fault behaviors and seismic hazard potential. Interseismic surface creeping of active faults may not only continually damage man-made structures but also influence the estimation of slip-deficit rates. Southwestern Taiwan is located on the orogenic front under the arc-continent collision between the Eurasian Plate and the Philippines Sea Plate, many active faults in this area pose a threat to the infrastructure and the safety of local residents. Various geodetic observations have been applied to capture the surface deformation induced by these active structures. Two large earthquakes, the 2010 ML 6.4 Jiashian earthquake, and the 2016 ML 6.6 Meinong earthquake, occurred in Southwestern Taiwan. One important question is how surface deformation changes in response to the earthquakes during the interseismic period.

In recent years, the Interferometric Synthetic Aperture Radar (InSAR) technique has become a more influential way for accessing high spatial resolution deformation patterns in a region. In this research, I utilized multiple sets of L-band SAR images, which are capable of penetrating vegetation, to investigate active structures in Southwestern Taiwan. We integrated the deformation time series from SAR with ground deformation data from continuous GNSS stations in the study region, constructing a ground deformation dataset for the periods 2007-2011 and 2016-2022. Several major active structures like the Houchiali Fault, the Chungchou Structure, the Hsiaokangshan Fault, and the Longchuan Structure, can be observed based on the InSAR line-of-sight velocities.

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Monitoring Coastal Land Subsidence in Western Taiwan by Using SBAS-InSAR Technique

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Abstract

Coastal land subsidence has been identified as one of the major global environmental issues. In Taiwan, the western coast has also experienced severe land subsidence due to rapid development and excessive groundwater extraction. However, the spatiotemporal patterns of coastal subsidence remain less understood. Thus, this study employed the small baseline subset interferometric SAR (SBAS-InSAR) technique with multi-mission datasets to reconstruct a quantitative history of coastal subsidence in western Taiwan over the past three decades. Coherence-based network modification and algorithms for unwrapping error correction were utilized to improve temporal coherence. Additionally, the effectiveness of tropospheric corrections and different phase deramping methods were also assessed.

Results identify Changhua County and Yunlin County as the primary areas experiencing coastal subsidence, with significant subsidence also observed in Chiayi County, northern Tainan City, and Pingtung County. Between 1995 and 1999, Dacheng Township in Changhua County experienced the highest line-of-sight (LOS) deformation rate of 6.0 cm/yr, while the northern part of the Sixth Naphtha Cracker Complex in Yunlin County experienced a rate of 5.3 cm/yr. From 2006 to 2008, the subsidence center in Changhua County shifted inland, with the coastal LOS deformation rate decreasing to approximately 2.7 cm/yr. Meanwhile, the subsidence center in the Sixth Naphtha Cracker Complex moved southward, with a maximum rate of 7.5 cm/yr. Deformation velocities in Pingtung and the northern part of Tainan decreased during this period. In the last observation period from 2014 to 2023, while subsidence rates in most areas within the low-elevation coastal zone have diminished, reclaimed lands and coastal Pingtung Plain have persisted with relatively high subsidence rates. These detailed monitoring data provide a chance to delineate potential inundation zones under different sea level rise scenarios.

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Geodetically Constrained Interseismic Deformation and Seismic Potential Along Frontal Taiwan Orogenic Belt

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Abstract

The orogenic belt is a picturesque, but also cruel region. The orogenic processes have shaped the diverse landscape of nature today, yet they come hand in hand with frequent hazardous earthquakes. The most active area of an orogen lies in the deformation front, where plates converge and collide over hundreds of kilometers in length and tens of kilometers in width, exhibiting immense energy and intense tectonic activities. The mountain topography constantly reminds us of the dangers inherent in mountain belts and their deformation fronts. Numerous studies aim to observe and assess these orogenic movements and the disasters they bring. Given the extensive scope of orogenic belts, a substantial amount of data is required to support research in this area, among which geodetic techniques play a crucial role. Through the utilization of GPS, leveling, and satellite technologies, geodetic methods aid in the study of deformation fronts in mountain belts.

Taiwan, situated atop an orogenic belt, experiences daily seismic activities that attest to the vigor of orogenic movements in the region. Several catastrophic earthquakes recorded throughout history continuously remind people not to underestimate these seismic events. The Changhua Fault, located on the western deformation zone of the orogenic belt, lies adjacent to the second most populous metropolitan area in Taiwan. Coupled with a possible historic earthquake of the fault occurred in 1848, which demonstrated its destructive potential, it demands particular attention. Therefore, this study will utilize geodetic data in conjunction with two-dimensional and three-dimensional numerical models to comprehend the Changhua Fault, aiming to understand its interseismic velocity and future seismic potential.

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以SBAS方法監測雲林地層下陷區域之水平大地變形

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摘　要

雲林位處濁水溪沖積扇南側，長期因超抽地下水而發生地層下陷，1992年至今累積下陷量已超過190公分。地層下陷伴隨而來的災害，如海水倒灌與建物受損，造成持續的經濟損失與風險，因此有必要持續對地層下陷進行監測，以作為地層下陷防治措施的參考。由於台灣西南部的降雨乾濕季分明，降雨集中於5月到9月，因此下陷主要發生於乾季期間，並在濕季降雨帶來地下水補注後減緩下陷速率，甚至發生地層回脹。近年來，雲林的下陷中心位於土庫及元長一帶，目前最大下陷速率超過60 mm/yr。除了垂直位移，下陷中心亦顯示與沉陷錐相關的水平位移，且變形速率隨乾濕季發生變化。

目前，許多研究已透過合成孔徑雷達干涉技術（Interferometric Synthetic Aperture Radar，InSAR）監測雲林的地層下陷，並與水準及GPS資料比對，證實InSAR有足夠精度進行地表變形監測。相較於水準及GPS等點狀監測方法，精度受限於點位密度，InSAR具有面狀監測的優勢，可有效掌握地層下陷的時空變化。由於InSAR量測到的數值為視衛星（Line of Sight，LOS）方向的變形，過去研究多透過假設水平位移為0，以將LOS方向變形投影到垂直向，因此缺乏對於此區域下陷相關水平變形的討論。

為瞭解地層下陷造成的水平位移，本研究使用2020年5月到2023年5月Sentinel-1衛星的升、降軌影像，利用短基線子集法（Small Baseline Subset，SBAS）進行時序分析。接著，本研究將林內國中GPS連續站設為參考點，獲得升、降軌LOS方向速度場後，以線性逆推將速度場投影至垂直向及東西向。InSAR初步結果顯示，位於土庫、元長一帶的下陷中心，可再分為東西側兩個中心，最大下陷速率超過90 mm/yr。在乾季期間最大下陷速率達 130mm/yr，濕季下陷速率則減緩至約50mm/yr。乾季期間在高鐵西側有向西40 mm/yr的變形速率，濕季時則在高鐵東側有向西70mm/yr的變形速率。

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A test of detect surface displacement in fast vegetation change area by using high resolution optical image: a case study in 2022 Taitung earthquake sequence

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Abstract

Detecting the distribution of coseismic slip patterns plays a key role in analyzing the fault geometry and tectonic implications. To detect the high spatial resolution distribution of surface displacements, optical satellite images are one major tool because of the large coverage of surface deformation areas. However, the subpixel correlation method, the most common surface displacement detection approach using optical images, becomes a challenge if the study area experiences rapid changes of land cover and long capture recurrence times. These challenges were faced in the case of the 2022 Taitung earthquake sequence, a series of earthquakes with magnitudes of Mw 6.4 and Mw 6.8 that occurred in the central Longitudinal Valley, which resulted in distributed surface rupture along the Yuli fault and the Longitudinal Valley fault. If we use the orthoimages captured by the high-resolution satellite, Pléiades, the affected area of the earthquakes changes significantly within 3 months because most areas are seasonal paddy fields, making the subpixel correlation difficult. Thus, a different method is needed for this event. In this study, we generated a detailed surface displacement field around the earthquake-affected area from the orthoimages captured by the Pléiades, both pre- and post-earthquake. By utilizing the image classification method, we classified the ground features in the orthoimages and measure the difference.

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利用地表變形時序探討2022年池上地震序列之發震構造

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摘　要

台灣東部縱谷地區位於歐亞板塊大陸邊緣和菲律賓海板塊上的呂宋島弧的碰撞邊界，為全球地震活動頻繁區域之一。2022年9月17日和9月18日在縱谷南側池上區域附近分別發生了Mw 6.4和Mw 6.6的地震，對縱谷中南部地區造成嚴重損害與地表破裂。對於區域內的縱谷斷層與中央山脈斷層構造，尚有許多不清楚的地方，若能有更多的地表變形時序資料，將有助於釐清其行為與機制。因此本研究選擇2021年9月至2023年9月超過100張的Sentinel-1雷達衛星影像，配合Small Baseline Subset（SBAS）方法，處理超過300對干涉圖幅進行分析探討。研究結果顯示，在同震變形上，地表變形主要在縱谷南部，並有明顯分段的特性，顯示在不同區塊上，兩發震構造的行為差異。在玉里地區震後變形上，利用升軌（Ascending）與降軌（Descending）所計算的Line of Sight（LOS）速度場進行二維向量（東西及垂直）分解，可明顯看出跨中央山脈斷層，依舊有明顯的速度差，在垂直向上可達10 cm/yr，表示此發震構造在震後持續在應力調整。然而，由於研究區域斷層和地質系統的複雜性，須進一步的分析和整合其他測地資料的必要性，以更全面地解釋縱谷中南部發震構造的行為和特徵。

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Investigating Surface Creeping in Southern Longitudinal Valley Fault by InSAR Time Series

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Abstract

Surface fault creep, a significant behavior related to seismic hazard assessments, releases energy through aseismic slip and can potentially lead to earthquakes. The Longitudinal Valley fault (LVF) in eastern Taiwan, situated within the active collision boundary of the Philippine Sea and Eurasian plates, is globally renowned for its observed surface creep with oblique motion in southern portion from Yuli to Lichi. Geodetic data indicate a reported surface creep rate of approximately 10-30 mm/yr at specific sites along the fault. InSAR time series using Envisat and ALOS-1 images also reveal substantial surface creep along the southern LVF. Despite widespread surface creep in geodetic data, in-situ observations do not consistently align with imaging geodetic observations, showing localized surface creep at specific locations. Moreover, fault creep patterns derived from InSAR time series exhibit variations over time. Hence, in this study we conduct a spatial-temporal analysis of southern LVF surface creep by using the Small Baseline Subset (SBAS) InSAR technique. Employing ISCE software, we preprocess, co-register, and apply DInSAR to 3 frames and 10 ALOS-2 SAR images in the ascending orbit in the stripmap (SM3) mode. The split-spectrum method is employed for ionospheric correction. The results reveal a velocity boundary ranging from 10 to 30 mm/yr in the line-of-sight (LOS) direction along the southern Longitudunal valley. The major velocity change boundary migrates westward in the southernmost valley, and a noticeable change in LOS velocity, approximately 8 mm/yr, is observed along the northern section of the Luyeh fault. Conversely, the southern part of the Luyeh fault does not display a significant difference in velocity. Instead, the neighboring Pinglang fault to the west exhibits a gradual velocity change of around 5 to 8 mm/yr.

key words: interseismic deformation、active tectonics、Chihshang Fault、surface deformation

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Land Subsidence Mapping in Jakarta Indonesia and its surrounding regions Performing Persistent Scatterer InSAR Technique

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Abstract

The investigation of land subsidence in Jakarta has been performed in different studies. There are adjacent regions of Jakarta experiencing different rates of land subsidence. This study investigates a spatiotemporal variation, the possibility of causes, and the long-term impact of the land subsidence in different locations of Jakarta, and its nearby. 125 sentinel 1A in ascending and descending images were used to calculate the land subsidence rates performing the Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) technique. A similar rapid land subsidence rate also occurs in two densely populated regions near Jakarta, which are Tangerang (belongs to Banten province) and Cikarang (belongs to West Java province) up to 70 mm/year. The highest rate of land subsidence occurred at 2021 that was estimated by Random Forest Regressor (RFR) algorithm. Near the coast, due to the rapid of the land subsidence, the seawater overflowed onto the land specifically at Penjaringan, north Jakarta called as tidal flooding. The combination of land subsidence and Sea Level Rise (SLR) cause a greater expansion of the flood area along the coast Jakarta and its adjacent regions. Due to of this circumstance, the infiltrated sea water has polluted the aquifer water at a depth of 0-40 m at some areas near the coast.

Keywords: land subsidence, PS-InSAR, Sea level Rise (SLR), groundwater quality.

Reduce Ionosphere Effect On 2022 Chihshang-Guanshan Earthquake

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Abstract

The DInSAR technique utilizes Synthetic Aperture Radar (SAR) images to assess surface deformation through phase differences. Its advantage lies in its ability to penetrate cloud cover, which obstructs optical imaging of target areas. However, SAR is still susceptible to errors beyond surface deformations, notably atmospheric effects. Atmospheric disturbances primarily stem from the ionosphere and troposphere, each governed by distinct mechanisms.

In this study, we investigate the seismic events that occurred around the Chihshang Guanshan areas on September 17th and 18th, 2022. These earthquakes, with a magnitude of Mw 6.53 and Mw 6.93, resulted in significant surface deformations, with field surveys documenting displacements of approximately 1 meter. We use SAR images from ALOS2 PALSAR-2 Strip Map(SM3) in ascending orbit, to mitigate the atmospheric effects, particularly ionospheric disturbances. To do that in our study we would use a method called Split-Spectrum Method(SSM), which won't acquire external ionosphere maps. We seek to assess the efficacy of these models in reducing tropospheric effects and determine their suitability for mitigating atmospheric disturbances in this specific seismic event.

Keywords:
ALOS2, PALSAR-2, DInSAR, Ionospheric Effects, 2022 Chihshang-Guanshan Earthquake

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基於集成學習與 GEE 的衛星影像土壤水分反演

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摘　要

在全球氣候變化的背景下，精確的土壤水分監測對於農業發展和自然災害監測變得尤為重要。傳統的遙感技術雖然在這一領域已有廣泛應用，但在數據處理效率和模型精度方面仍存在不小挑戰。針對這些問題，本研究引入了一種結合 Google Earth Engine（GEE）雲平臺和集成學習的創新方法，旨在利用衛星遙感影像實現高效且高精度的土壤水分快速反演。本研究的創新之處在於兩個方面：一是通過 GEE 平臺的應用，我們突破了數據處理的瓶頸，實現了對大規模數據點以及其多特徵因數的的快速準確處理，為土壤水分監測提供了更為豐富和準確的數據基礎；其次，集成學習的應用優化了預測模型的性能，通過綜合多個演算法的優勢，顯著提高了反演精度，且結合 GEE 所處理的大量樣本點及多特徵因數，有效避免了因數據量不足而導致的模型欠擬合問題，提升了土壤水分反演的精度和模型的泛化能力。本研究提出的方法不僅能為農業規劃和災害管理提供更準確的數據支持，也展現了利用 GEE 平臺和集成學習技術在環境監測領域的巨大潛力。

關鍵字：衛星遙感，土壤水分，GEE，集成學習

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Soil Moisture Retrieval with Satellite Images Based on Ensemble Learning and GEE

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Abstract

In the context of global climate change, accurate monitoring of soil moisture has become particularly important for agricultural development and natural disaster monitoring. Although traditional remote sensing technology has been widely applied in this field, there are still significant challenges in terms of data processing efficiency and model accuracy. To address these issues, this paper introduces an innovative approach that combines the Google Earth Engine (GEE) cloud platform with ensemble learning, aiming to utilize satellite remote sensing images for efficient and high-precision rapid retrieval of soil moisture. The innovation of this research lies in two aspects: firstly, by applying the GEE platform, we have broken through the bottleneck of data processing, achieving rapid and accurate processing of large-scale data points and their multiple characteristic factors, which provides a more abundant and accurate data foundation for soil moisture monitoring; secondly, the application of ensemble learning has optimized the performance of the prediction model. By integrating the advantages of multiple algorithms and combining with the large number of sample points and multiple characteristic factors processed by GEE, it effectively avoids the model underfitting problem caused by insufficient data volume, improving the accuracy and robustness of soil moisture retrieval. The method proposed in this paper not only provides more accurate data support for agricultural planning and disaster management but also demonstrates the great potential of using the GEE platform and ensemble learning technology in the field of environmental monitoring.

Keywords: Satellite Remote Sensing, Soil Moisture, GEE, Ensemble Learning

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多光譜無人機精密監測之應用-以茶園為例

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摘　要

在全球氣溫升高且氣候變遷不斷加劇的現況下，減少碳排放已成為當前迫切需解決的議題。植物作為地球碳循環系統的重要組成部分，其生長狀況的精確監測對於評估相關資訊至為關鍵。然而，近年來頻繁發生的極端氣候事件，特別是全球性的氣象異常，如 2021 年臺灣遭遇的嚴重旱災，3 月至 4 月間完全沒有降雨，直到 5 月才開始下雨。這樣的乾旱環境對茶樹造成了嚴重的影響，導致茶樹死亡和葉片掉落，茶葉產量也減少了近一半。此種背景下，亟需有效的監測方法來應對氣候變遷所帶來的挑戰。在過往的監測方法中，常使用航照、衛星影像（解析度較低）或人力調查（耗時費力）。然而，近年來，無人機技術的快速發展提供了取得高解析度影像的新途徑。結合多光譜鏡頭，這些影像還可以用來計算植生指數，拓展了監測應用的多樣性。本研究以番路鄉隙頂茶園為例，引入自動圈繪技術，能夠迅速估算茶樹面積。同時，我們使用了常態化差異植生指數（normalized difference vegetation index，NDVI）來與茶葉產量做比較，結果顯示兩者呈現高度正相關。由於無人機的機動性，我們可以根據不同需求和目的，靈活地進行影像拍攝，提供即時且多元的資訊，意味著更有力地應對氣候變遷對植物健康的不確定性。

這種高精度的監測方法也可應用於生態多樣性保護、森林火災預防等領域，同時提供政府制定更為有效的環境政策的關鍵科學數據。若能透過多光譜無人機建構完整的資料庫並實現自動化處理系統，將為氣候變遷相關分析和政策討論提供更為全面的科學基礎和豐富的資訊。

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Topographic Reconstruction of Dahan River Terraces by Using Historical Aerial Images

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Abstract

Terrain analysis is a method used to explain the formation and evolution of landforms. By analyzing the topographic features of river terraces, we can infer the past channel positions and understand the uplift and deformation caused by regional tectonic activities. In our study area, the Dahanxi River Terrace is located in Taoyuan, which is the largest river terrace group in northern Taiwan, extending from the Jiaobanshan area to the Yingge area. The Dahan River has experienced significant incision and formed widespread river terraces due to the orogenic activity in northern Taiwan and the subsidence of the Taipei Basin. Therefore, analyzing the Dahan River Terrace is crucial for understanding the regional structural characteristics. However, because of the construction of the Shimen Reservoir in 1964, a portion of the Jiaobanshan River Terrace submerged. Consequently, the current digital terrain models and images cannot fully present the terrain of the Dahan River Terrace. Historical aerial images become valuable resources for recording the topography of the Dahan River Terrace. In this research, we used historical aerial images of the Dahanxi River from 1957 and combined them with the Structure from Motion (SfM) technique to reconstruct a three-dimensional topographic model. Initial outputs include a digital surface model (DEM) and orthoimage with an error range of 6 to 8 meters. From the SfM-generated DSM, the original topography of the Jiaobanshan area is visible and reveals the additional river terrace.

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Geology structural identification through 3D Resistivity Inversion of Magnetotelluric (MT data in the Tatun Volcano Group (TVG, Northern Taiwan

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Abstract

Understanding subsurface electrical conductivity is paramount for characterizing geothermal settings, with Magnetotelluric (MT) methods serving as a cornerstone in geothermal exploration. This research focuses on the Tatun Volcano Group (TVG) in Northern Taiwan, employing advanced geologic structural identification through the 3D resistivity inversion of MT data. The comprehensive geophysical dataset, comprising 49 MT measurement stations, amalgamates information from both the ITRI (Industrial Technology Research Institute) and Computational Geophysical Research Group (National Central University) datasets. A meticulously developed 3D resistivity model, inclusive of resistivity cross-sections and maps at varying elevations, serves as a robust tool for identifying anomalies critical to conceptual models guiding future production field expansion. Noteworthy outcomes of this study include the delineation of three potential geothermal areas and their heat source within the 3D resistivity model. These areas are characterized by a distinctive geological profile, featuring a low-resistivity clay cap juxtaposed over a high-resistivity core. Of particular significance is the identification of the heat source as a hot dry igneous body with high resistivity, high density, and high susceptibility located 5 km beneath the southwestern region of the TVG. Emphasizing the geological significance of subsurface conductivity, this study advances the understanding of geothermal systems in the context of the Tatun Volcano Group.

Keywords: Tatun Volcano Group (TVG), geothermal exploration, Magnetotelluric (MT), 3D Resistivity

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利用福爾摩沙陣列探討臺北都會區之微震特性

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摘要

本研究利用由中研院地球所林正洪老師團隊佈設和維持的福爾摩沙陣列(Formosa Array, FA)，在台北都會區共 114 測站於2019年的連續資料，我們首先在時頻圖中發現較強信號發生在 2-20 Hz、1-0.05Hz 這兩個頻率段，對應到microtremor和microseism兩種訊號，其中microseism內又以secondary microseism (SMS，0.25-1Hz)頻段有能量明顯的訊號。利用一整年的資料計算每日中位數後，進行各測站的振動趨勢比較，我們發現 SMS在FA各區不同測站有「時間同步」之特徵，說明對應之振動源發生的空間範圍相對寬廣，影響著所有測站在低頻段(< 1 Hz)的振動表現。SMS的重複特性呈現的時間趨勢具有 6-10 天的重複性。為了進一步釐清可能的控制因子，我們將 FA 測站的連續振動紀錄與氣象/潮汐數據間之滑動交相關係數計算，發現振幅最大值與陣風，氣溫氣壓，海浪潮高有關，且不同區域測站各參數的影響權重不同。此外颱風與季節循環也明顯影響SMS振幅每日最大值的表現。振幅中位數記錄則與氣壓具有較高之相關性，而非潮汐起伏，這說明大氣和海洋的耦合現象對微震的發生扮演重要的角色，如何分辨各自的影響力以至於將微震行為應用至判斷、偵測環境訊號，有待進一步的探究。

【學生壁報比賽】參與者於摘要尾端註記

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Investigation of Permafrost by Using Electrical Resistivity Imaging and Ground Penetrating Radar: A Case Study in Svalbard, Norway

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Abstract

Over the years, climate change has significantly impacted the global ecological environment, with the polar regions being among the first to experience changes. Not only the environment above the surface has been affected, but also the subsurface. This study aims to characterize and find the interaction between the permafrost and active layer, by implementing Electrical Resistivity Imaging (ERI), and Ground Penetrating Radar (GPR). Along with the Nicolaus Copernicus University team, this study is eager to learn about this phenomenon in the Svalbard Archipelago, Norway. We collected the data by employing a Wenner array configuration using 40 electrodes with 1m spacing for the ERI, and a 100 MHz antenna frequency for the GPR. The profiling line is about 140 meters from the station and extends forward to the coast. The data were collected in 2022 and 2023, in order to observe the variation and behavior of the subsurface. Furthermore, the ERI and GPR results were integrated with groundwater level and temperature distribution data to enhance the result. Thus, a comprehensive understanding of the subsurface changes due to climate changes can be obtained. In summary, our geophysical approaches have proven to be a powerful tool for this purpose.

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Developing a Deep Learning-Enabled Taiwan Transformer Shaking Alert Model (TT-SAM and Its Implementation

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Abstract

In this study, we have referenced the Transformer Earthquake Alerting Model (TEAM), a deep learning earthquake early warning (EEW) framework. We optimized the model using seismic data from Taiwan to develop the Taiwan Transformer Shaking Alert Model (TT-SAM), and it could rapidly calculate the seismic intensity to provide longer lead time. We utilized the Taiwan Strong Motion Instrumentation Program (TSMIP) database to obtain waveforms for events with a magnitude greater than 3.5 that occurred between 1999 and 2019. We split the dataset for model training and testing, the observations in 2016 were separated individually for the final evaluation. We cut the waveform initially triggered by the P-wave into a time window of 15 seconds, and other triggered stations' waveforms in these 15 seconds will also be included. The model extracts waveform features through a convolution neural network (CNN), while the transformer encoder builds the relationship between features and station location. At the end of the model, we used a mixture density network to predict ground shaking by probability density functions. We set a warning threshold at 25 cm/s^2 in PGA, corresponding to Central Weather Administration (CWA) intensity IV, to validate the model's performance with 2016 data. The result shows that precision and recall are 75% and 81%, respectively. It's noteworthy that the average lead time for the 2016 M_w6.4 Meinong event and M_w6.1 Taitung offshore event stand at 16 and 7 seconds, respectively. In addition, we also analyzed the correlation between the feature map from CNN and other physical attributes, e.g., waveform envelope and Euclidean norm. This study is conducted in partnership with the CWA Seismological Center to implement TT-SAM as a real-time earthquake early warning system. The objective is to improve the efficiency and dependability of AI-based EEW in Taiwan.

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深度學習地震監測系統應用在不同地震網的地震目錄

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摘　要

SeisBlue 是一個使用深度學習模組的地震監測系統，可以用於處理大量的地震連續波形並產生地震目錄。SeisBlue 的處理流程包含波形資料的預處理、使用 AI 的波相偵測、波相關聯、地震定位、產生地震目錄和資料視覺化。全部的過程可以自動化進行，節省人力和運算時間。本研究使用 SeisBlue 測試三種不同的測站密度地震網以實測了解 SeisBlue 的處理效能。第一個測試地震網為 FORMOSA 寬頻地震網，其目的為監測大屯火山之下岩漿庫，其地震網半徑約 80 公里，共設置 148 個測站，測站間距為 5 公里。第二個測試地震網為 ETBATS 寬頻地震網，為監測台東池上地區孕震帶的地震網，其地震網半徑約 150 公里，共設置 14 個測站，測站間距為 5 公里。最後一個地震網為 2022 年 9 月 18 日芮氏規模 6.9 池上地震餘震序列的臨時密集網，其地震網半徑約 70 公里，共設置 46 個測站，測站間距維 3 公里的臨時 SmartSolo 地震站。測試結果顯示，使用 SeisBlue 處理 FORMOSA 陣列的 2020 年資料，我們共偵測到了 2,201 個地震，而同時在中央氣象署的地震目錄則共列出了 1,467 個地震。應用在池上地震網的資料結果 SeisBlue 共偵測出了 14,276 個地震，而中央氣象署的地震目錄則僅列出了 1,427 個地震。而在 2022 年 9 月 18 至 10 月 25 日，我們同時建置了臨時密集網和池上寬頻地震網(ETBATS)，可以藉此比較測站間距與地震偵測數量之相關性，結果顯示對臨時密集網和池上地震網使用 SeisBlue 分別可以偵測到 34,630 和 12,458 個地震。從三個測試結果顯示，SeisBlue 可以有效率的偵測出背景地震和餘震序列，使用密集地震網的資料可以偵測到更小的地震。

關鍵字： AI 地震監測系統、深度學習、AI 地震目錄、SeisBlue、自動挑波

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Riverbed grain size survey using deep learning model and RGB-D images

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Abstract

The water level and discharge of river are crucial parameters to understand the variance in riverbed scour. The detail behavior of scouring can be studied by the hydraulic simulation. The grain-size distribution of riverbed is also one of crucial parameter for modeling. Thus, how to investigate the grain-size of riverbed efficiently and swiftly is the urgent issue. However, the conventional measurement methods including Wolman counts (particles sampled at a fixed interval) which are a long and laborious task cannot survey the grain-size efficiently in the large area. In recent years, with an advantage of image segmentation and recognition has been applied to the investigation of grain-size, for example, capturing images through UAV and generating orthoimage is one of commonly used image technique. Although above the method can investigate the grain-size in the large area, it does not provide the information in the field immediately. Hence, a recent study developed the low-cost portable scanner to obtain the information of grain-size distribution in the field. However, the calibrating parameters of camera (e.g., height camera capture) are necessary before survey, and the uncertainties in calculation of image resolution will significantly affect the accuracy of grain-size analysis. Furthermore, most 2D image recognition relies on the features of RGB grayscale values, making it challenging to capture color variations and texture details in complex scenes, resulting in ineffective detecting both the larger and smaller grain sizes. Above limitations can be observed in analysis examples of Pebblecounts and Imagegrains (Figure 1a, b) and Imagegrains (Figure 1c). Both open-source software of Pebblecounts and Imagegrains cannot comprehensively capture all grain particle, especially for large grain-size particles (Figure 1d). Therefore, this study provides the additional algorithm to analyze the grain-size by using RGB-D image as inputs. The application of RGB-D can be categorized into two-dimensional (2D) and three-dimensional (3D) spaces. In this study, Intel RealSense depth camera D435 is used to capture RGB-D images (Figure 2; RGB and depth images). In a case of 2D, it reserves depth-sensitive regions, which would be available to separate the grain-size of riverbed from the background (e.g., bottomland). With the available regions and RGB images, the algorithms of image pre-processing (e.g., smoothing, denoising and Otsu-threshold), edge detection (e.g., tophat, sobel) and ellipsoid fitting were adopted to measure the particle diameters and provide grain size distribution. In a case of 3D, the collected RGB-D image information is transformed into point cloud data, then extract 3D features of grain particle by Deep learning, specifically PointNet. Our study demonstrates that clustering of 3D features can achieve the automatic identification of particle. The grain-size of particle can also be estimated by fitting 3D ellipsoid geometry. In the end, results show the grain-size distribution curves with the RGB, RGB-D, PointNet recognition, and compare with the true observations. 3D image information provides the cloud points of grain object, leading the possibility of estimating the 3D geometric morphology of the object. Our study successfully

overcomes the limitations of conventional RGB-based process, which could only capture size and shape information in 2D planar. RGB-D-based image recognition is an innovative technique for the hydraulic problem, not only advances survey efficiency but also addresses the intricate steps required for field investigations.

Key words: Riverbed grain-size, RGB-D image, Point cloud, Deep Learning

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SeisBlue AI地震資料處理平台的技術實踐

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摘 要

本研究旨在應對密集地震網和地震資料量劇增所帶來的挑戰。我們利用深度學習技術，致力於提升地震資料處理的自動化程度和效率，並考量了台灣獨特的地下構造，訓練與調整深度學習模型。自2018年以來，SeisBlue 已開發到第三代，我們採用 Transformer 模型並結合生成對抗式網路 (GAN) 的訓練技術做地震挑波，並整合關聯和地震定位。至今，最新一代的系統加入新開發的 SeisPolar 模型來分類地震波初動極性，進而解析高準確性的震源機制解，持續擴展 SeisBlue AI 地震資料處理平台的功能與優化流程。

此外，軟體品質和非功能設計的部份，我們以資料管線為主軸重新設計整體系統的自動化流程，並從 TensorFlow 轉換到 PyTorch 深度學習框架。系統在實現過程中廣泛借鑒了資訊工程方面的技術，整合了硬體、系統環境、資料庫、資料管線、模型開發、任務監控以及資料可視化、Web UI 互動等多方面技術。

目前已實現了從地震連續資料處理到挑波、定位、規模計算及震源機制解析的半自動化流程，大幅提升地震資料處理的效率，為後續的研究提供高效與可靠的地震目錄。

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利用SWMM模式評估低衝擊開發的減洪效益
-以台中市沙鹿區為例

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摘　要

隨著社會經濟的現代化發展，都市人口及建築物不斷增加，意味著原先自然覆蓋的土地逐漸由不透水的房屋及道路所取代，降雨至地表後因入滲與截留變少，逕流量增加，當暴雨事件來臨時超過區域排水能力，將帶來低窪地區的水患。沙鹿位於大肚台地西側，為梧棲排水（區域排水）的上游。區域內地形主要為台地和平原，台地平均高度為 200~300 公尺，於市區東側與平原接壤，平原海拔只有 5.1 公尺至 2.2 公尺。當暴雨來臨時洪水會延著台地上的野溪進入山腳下。由於坡度較陡山洪流速較快，當洪水由台地進入地勢平緩的市區時，會導致排水不及以致沙鹿成為易淹水地區。

在氣候變遷下，降雨將變得更極端，超過既有防洪設施標準的事件變得更頻繁，傳統防洪工程手段已無法因應氣候變遷所帶來之衝擊。此研究蒐集研究區內基本的水文、地文及下水道等基礎資料，並利用美國國家保護局開發的暴雨管理模式（Storm Water Management Model, SWMM），建立研究區的模型進行模擬，最後藉由 SWMM 探討設置低衝擊開發（Low Impact Development, LID）的設施能否提升土地的耐淹能力。

研究中藉由觀測資料發現，近幾年的暴雨事件中，排水測站洪峰水位為 0.4 公尺至 0.9 公尺，與警戒水位 2.8 公尺有些落差；另外藉由 SWMM 模擬也發現從上游進入雨水下水道的地表逕流量並不足以造成溢流。因此初步了解上游溪流並不是影響市區淹水的主要因素，而是降雨超過市區街道側溝的保護標準，逕流進入地勢較低的沙鹿市區時，無法順利地將水排出，因此探討不同面積的 LID 設施及空間分布差異下，對街道排水分區逕流削減之效益會是本研究的一大重點。希望研究區可以透過建置永續且具有災後復原能力的基礎設施，減少自然災害帶來的衝擊，使居住環境提升面對災害的韌性。

關鍵字：低衝擊開發、SWMM、淹水、暴雨逕流

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A Two-Dimensional Semi-Analytical Model for Multispecies Transport Affected by Rate-Limited Sorption with Decay in Solid Phase

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Abstract

In addition to advection and dispersion, which are considered the two main processes, sorption and degradation/decay are also crucial in contaminant transport models. While many models assume equilibrium-controlled sorption, rate-limited sorption may be necessary in some cases. Similarly, degradation, often assumed only in the aqueous phase, must consider solid-phase decay for certain contaminants like radioactive waste. This study develops a two-dimensional model for multi-species contaminants under the influence of rate-limited sorption with decay in the solid phase. The multispecies contaminant transport in the aqueous and solid phases is represented by the advection-dispersion equation (ADE) and using different time-dependent input conditions. The multispecies pollutant simulated in this study is radioactive waste, consisting of four species: Pu^{238}, U^{234}, Th^{230}, and Ra^{226}. The model compares the concentrations of contaminants belonging to the decay chain in two scenarios: one in which the decay occurs exclusively in the aqueous phase and one in which the decay occurs in both the aqueous and solid phases. The results show that the concentration of the first contaminant in the decay chain (Pu^{238}) tends to decrease when considering the decay process in the solid phase. Meanwhile, with the contaminants formed through the decay process (U^{234}, Th^{230}, and Ra^{226}), their concentration significantly increases when decay occurs in both phases. This demonstrates that not considering the decay process in the solid phase can lead to an erroneous assessment of contaminant concentrations in groundwater, especially for hazardous contaminants such as radioactive waste.

Keywords: semi-analytical model, decay in solid phase, rate-limited sorption, radioactive waste

Apply THMC to simulate the porosity reduction in a porous reactive barrier aquifer system

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Abstract

Permeable reactive barrier (PRB) involving zero-valent iron (ZVI) is an in-situ technique for treating groundwater contaminants. Chemical reactions take place inside the PRB, promoting secondary mineral precipitation and leading to a decrease in the porosity of the PRB. When the porosity reduction, flow path reorientation, residence time changes, and bypassing occur. This study used THMC software, a numerical model of Thermal-Hydrology-Mechanical-Chemical (THMC) through multiple phases, to determine porosity reduction through flow modeling and the chemical reactions occurring within the PRB. According to the groundwater flow model, PRB has a permeability higher than the neighbouring aquifer materials, allowing water to pass through quickly and preserving the groundwater's hydrogeology despite removing contaminants. The model result indicates that porosity loss is most significant at the entrance face (0.0138), followed by a fall and stabilization after 0.2 m at the PRB entrance. Aragonite, siderite, and ferrous hydroxide reduce porosity by more than 99%. This model highlights the relative effect of concentration by illustrating porosity losses for the high and low levels of bicarbonate and sulfate in the entering groundwater. The concentration of bicarbonate has a significant impact on the reduced porosity caused by the formation of precipitated carbonate minerals. The rate coefficient also influences porous reduction, while the anaerobic iron corrosion rate coefficient is highly sensitive to porous reduction due to iron corrosion influencing the formation of Fe^{2+}, OH^-, and the precipitation of $Fe(OH)_2$. Therefore, this research aims to use THMC to simulate the decrease of porosity in PRB, investigate the factors that should be considered when predicting porosity loss from mineral clogging in PRB and analyze the reduction of porosity over time.

Applying the three-dimensional variably saturated flow model to simulate groundwater flow in Pingtung plain by using THMC

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Abstract

Pingtung Plain is an agricultural area in southern Taiwan, that is recorded as having the lowest rate of tap water usage in all of Taiwan. Overexploitation of groundwater in this area has led to a drawdown in overall groundwater levels, seawater intrusion, and land subsidence. Additionally, this is an area with high rainfall, and the terrain is conducive to the creation of groundwater. However, constructed objects like roads and buildings have an impact on surface permeability, which is crucial for rainfall infiltration into groundwater. This study uses THMC (Thermal - Hydrology - Mechanics - Chemical) to simulate groundwater flow in the Pingtung plain using the variably saturated flow model. THMC model is water environment software developed by Prof. Gour-Tsyh Yeh and continuously expanded with a user-friendly interface platform by the CAMRDA team. With the aim of conducting regional groundwater flow modeling in Pingtung Plain, a 3-D finite element method flow model is established by using the interface of the THMC platform. The procedure includes determining the two-dimensional boundary of the study area combined with borehole and geological data under mesh generation. Then assign material properties and set hydrogeological parameters for simulation. The simulation first runs in a steady-state condition, then the result is input into the transient simulation as the first day of the simulation time period. Comparing and minimizing the differences in groundwater levels between observation data and simulation data is a calibration process for the developed model.

以熱示蹤劑試驗與模式評估海岸帶含水層分層流動特性

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摘要

隨著沿海地區經濟日益發展，海岸環境退化的問題逐漸浮現。為改善此現象，了解沿海含水層與海水間動態交換的過程，必是後續管理及規劃沿海含水層不可或缺的一環。本研究的目標是結合創新的現地試驗及三維數值模擬，以此評估臺灣西北部桃園台地沿海含水層的熱和水相互交換過程。為獲取此地分層流動和熱能傳遞特性，我們先在試驗場址內進行水力試驗及熱示蹤劑試驗，後運用 MODFLOW 和 MT3DMS 兩種數值模型，模擬出海淡水交互作用對沿海含水層溫度場的影響。此模型使用中央大學 TaiCOAST 臨海觀測站所獲取的地下水位和溫度觀測資料進行校準。現地試驗結果表明，主動式熱示蹤劑試驗所產生的熱響應與鑽探岩心匹配，並可藉此計算出此地地下水通量，此外，加熱井附近的觀測井，從地下水面到深 12 米間皆有顯著的熱反應，其中，觀測井 BW08 整體反應最為顯著。數值模擬結果與所觀測水位和溫度十分吻合，此模型以三維的形式解析此地地下水流動特性，並可用來計算地下水流速和估計熱傳導係數。模擬結果以高空間解析度揭示潮汐變化對沿海含水層的動態影響，為了解沿海含水

層系統的地下水排放情況提供了寶貴的見解。

關鍵字: 跨孔加熱試驗、海岸帶含水層、數值模式、分散式光纖溫度感測器。

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Revisiting ultra-rapid surface deformation in SW Taiwan using GNSS and ALOS-2 InSAR data

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Abstract

Southwest Taiwan, located at the end of the Western Foothills, is mainly composed of a thick mudstone layer. Two spot-like ultra-rapid surface deformation areas aligned north to south have been identified by the ALOS-1 InSAR result, situated between the Chegualin fault (CGLF) to the west and the Chishan fault (CSNF) to the east. The geodetic observations collected at the northern spot, located at the northern entrance of Chungliao Tunnel, National Freeway No.3, reveal a vertical velocity difference of approximately 90 mm/yr and a horizontal rate change of 20-30 mm/yr, which are larger than the plate convergence rate in Taiwan. However, is the southern ultra-rapid deformation spot located at the Hsin-young-nu-hu area reliable? Why did the ultra-rapid deformation occur at these two locations? To better quantify the local surface deformation, 6 continuous GNSS stations were installed at the southern and 6 at the northern spot since 2020. GNSS processing was carried out using the Pride-PPPAR software with Precise Point Positioning (PPP). In the northern spot, the horizontal velocity is approximately 30-40 mm/yr across the CSNF. The area between two faults experiences significant uplift, with around 40-50 mm/yr. To identify the spatial continuities between two spot-like areas, further InSAR processing was conducted using 11 ascending ALOS-2 images from 2015 to 2022 to improve the spatial resolution of surface deformation in this region, and 21 descending ALOS-2 images from 2015 to 2021 to improve the temporal resolution of InSAR data. The ISCE2 was employed for interferogram generation, and the Mintpy was utilized for time series analysis. The step function is adopted while estimating the velocity field to avoid the coseismic effect from the 2016 Meinong earthquake. We introduced a *priori* fault locations by setting the temporal coherence to correct the unwrapping errors during the default process from the ISCE2 using the SNAPHU. Then, the continuous LOS velocity pattern of around 30-40 mm/yr is shown in a few-hundred-meter narrow band between two faults. The LOS velocity gradient of around 20-30 mm/yr is shown across the two faults. In the southern part, the high deformation gradient is well consistent with the CSNF, and deformation along CGLF in the northern part is broader and appears to continue northward to the Longchuan fault. These observations provide precise constraints on the tectonics, enhancing the interpretation of this area. This ultra-rapid deformation identified in the narrow zone agrees that the hypothesis of mud-cored anticline or mud diapir that developed with two thrusts accompanying with the fault activities in the thick mudstone formation in SW Taiwan.

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應用深度學習類神經網路法於地震儀與電信光纖聯合密集陣列進行嘉義地區之微震偵測與定位

Using deep learning neural network method with combined geophone and dark fiber dense arrays for microseismic detection in the Chiayi area

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摘　要

台灣位處於歐亞板塊與菲律賓海板塊交界帶，因為板塊擠壓、碰撞頻繁，產生許多地震活動。在 2023 年 9 月 5 日於嘉義新港地區發生規模 5.5 的地震，一個臨時的密集地震監測網於該地區進行監測，並運用中華電信的電信電纜作為光纖陣列加入進行聯合觀測。分散式光纖感測技術是一種用於地震監測的新興技術，其優勢在於擁有高解析度，以及對微小震動有更寬頻的敏感度，在微震訊號上可以提供更連續完整的波場資料。由於此區域有梅山斷層通過，並在 1906 年曾發生規模 7.1 的強烈有感地震，然而經過百年之後，雲嘉南地區並未發生大規模地震，過去許多研究和調查也顯示此區域擁有極高的災害地震潛勢。

近年深度學習類神經網路法已在地震波相撿拾取上取得巨大的成功，高度自動化過去原本依賴人工經驗與耗時的作業流程，在很多區域的應用上建立了更完整的地震目錄。本研究即利用已被廣泛使用的 PhaseNet 深度學習波相撿拾器於新港地區短期架設的三分量地震儀及光纖陣列的連續記錄上，從波形的連續記錄中搜尋撿拾微震訊號的 P、S 波到達時間的機率分布，再進行微震定位，並比較光纖跟地震儀資料的相位挑選時間與機率分佈是否類似。預期光纖陣列的加入能幫助更準確地辨識和標記地震相位，提高地震定位的品質。透過分析定位結果有助於了解此區梅山斷層帶的地震活動、孕震帶構造特性及評估地震災害。

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Using distributed fiber-optic sensing for high-resolution mapping of structural characteristics of the Shanchiao Fault in Taipei metropolis

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Abstract

The Sanchiao Fault is an active normal fault located at the boundary between the Taipei Basin and the Linkou Tableland. It is capable of generating M 6+ earthquakes and is a major threat to the highly populated Taipei capital. However, the geometrical and structural characteristics of the Sanchiao Fault are not well understood due to the absence of outcrops covered by Quaternary alluvial deposits and the lack of high-resolution seismic data. Its east-dipping fault plane may extend beneath the urban area and cause devastating damage. The presence of soft sediments within sedimentary basins and the complex structure of the fault zone both play key roles in modulating seismic waves, resulting in strong amplification and prolonged duration of ground shaking. Here, we employ the emerging Distributed Acoustic Sensing (DAS) technology to turn an existing telecommunication cable (owned by Chunghwa Telecom Company) across the Sanchiao Fault into ultra-dense linear array to investigate the fault and basin structure at unprecedented meter-scale resolution. The high spatial resolution of DAS warrants the feasibility of array-based methods. In this study, we use the ambient noise cross-correlation and beamforming analysis to measure Rayleigh-wave phase velocities at various frequencies along the cable. The derived phase velocity profile (while yet inverted for shear-wave velocity) shows clear velocity contrast between the Taipei Basin and the Linkou Tableland, delineating a clear east-dipping geometry of the Sanchiao Fault. Future work will utilize phase velocity data to invert for high-resolution shear-wave velocity imaging across the fault to further our understanding to the dip, width, and degree of deformation of rocks within the fault zone, shedding insight into the earthquake rupture process and better assessing its seismic hazards. Our study evidences that DAS is a powerful new technology that can offer high-resolution mapping/monitoring of the major fault structures.

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Mineralogical and microstructural characteristics of active fault zone of the Milun Fault, and their implications

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Abstract

The Milun fault was triggered by the Hualien earthquake (M_w 6.4) and ruptured in 2018. The Milun fault has ruptured in 1951 and is therefore considered to be an active fault with a short recurrence interval. However, the fault-zone characteristics of the Milun fault remain unknown due to the lack of an exposed fault zone. The Milun fault Drilling and All-inclusive Sensing (MiDAS) project was designed to penetrate the active fault zone of the Milun fault and to deploy multiple monitoring systems. Here, we characterize the fault zone from the MiDAS using microanalytical methods, including optical microscopy, scanning electron microscopy, transmission electron microscopy, in-situ synchrotron X-ray diffraction and particle size analysis. The Milun fault zone is sandwiched by the Milun conglomerate in the hanging wall and footwall. The Milun fault zone is characterized by both variable widths of anastomosing clay-rich zones within spotted schists and dark grey gouges. In particular, multiple black gouge layers are observed as either fault veins or injection veins. The mineral assemblages of all samples include quartz, feldspar, carbonates, chlorite, and illite, while graphite and amorphous materials are observed within the black gouge. The black gouge contains reduced-size grains with flow-like structures as well as nanoscale fibrous structures. These observations suggest strain localization and frictional heating within the black gouge. The slip zone of the Milun fault is potentially identified, and its features can shed light on documenting the ancient coseismic events and the underlying earthquake physics.

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Comprehensive Characterization of the Milun Fault Zone in Taiwan using Fiber Optic Seismographs and 2-D Finite Difference Model

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Abstract

Fiber optic sensing, also referred to as Distributed Acoustic Sensing (DAS), has emerged as a vibrant area within seismology due to its high spatial resolution and adaptability to diverse environments using fiber optic cables, offering advantages over traditional seismometers. This study leverages data from fiber optic seismographs deployed as part of the Milun fault Drilling and All-inclusive Sensing project (MiDAS) initiated in 2020 in the Hualien region, alongside nearby conventional seismometer stations. Through comprehensive waveform characterization analysis of seismic waves propagating to the Milun Fault, we specifically investigate surface waves resulting from the conversion of body waves propagating to both sides of the fault upon reaching it, known as converted phases. This analysis is complemented by 2-D Finite Difference simulations aimed at replicating the actual structure of the Milun Fault. Incorporating various fault structures and velocity models, our simulations aim to mimic the authentic conditions of the fault. Moreover, we observe that the inclusion of a shallow velocity model of the Hualien region in our simulations reveals layer reflections generated by velocity interfaces appearing behind the S waves. Similar wave phases are also identified in observation data from MiDAS. Additionally, the utilization of the Slant Stack method significantly aids in identifying wave phases in the observation data. Overall, integrating fiber optic seismometers offers a pathway to overcome limitations in resolving subtle structures that were previously constrained by traditional seismometers. Through the combined analysis of fault zone converted phases, layer reflections, and 2-D Finite Difference simulations, our study provides valuable insights into the structural aspects of the Milun fault zone.

Key Words: Distributed acoustic sensing, Fault zone converted phase, Finite Difference Method

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台灣高山小河系統之氣體交換速率

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摘要

全球的碳循環中河流系統不僅傳輸有機與無機碳至海洋，也是二氧化碳排放的重要碳源。前人研究估算河流系統的二氧化碳排放量約每年 1.8 Pg，其中高山小河的通量約為每年 0.45 Pg，佔河流碳總通量的 25% (Raymond et al., 2013)，是不容忽視的重點區域。二氧化碳通量可由氣體交換速率與水中二氧化碳分壓計算而得，其中山區流域的氣體交換速率的量測資料因不易到達而十分有限，前人研究多使用大河系統模型之氣體交換速率進行估算，導致低估小河系統的碳排放量，更因此無法透過通量觀測解析控制機制。

有鑑於此，本研究測量台灣小河流域的氣體交換速率，並統整前人觀測資料以驗證各種預測模型，進而更精確估算河流系統碳通量。本研究於北勢溪流域的六條小河釋放兩種氣體示蹤劑（氪氣和丙烷），並測量不同距離下的溶解氣體濃度，利用濃度減少的比例計算氣體交換率。本研究亦同步釋放二氧化碳，以完善現地量測與採樣之設計，並了解二氧化碳示蹤之可行性。為了解不同水文下氣體交換速率的變異情況，本研究也測量河段深度剖面、流速及流量。結果顯示，相同河段三種氣體所得之氣體交換速率誤差於 30%內。氪氣所得之氣體交換速率介於 11.3~58.8 m d^{-1}；丙烷所得之氣體交換速率介於 17.3~81.8 m d^{-1}；二氧化碳所得之氣體交換速率介於 20.9~57.9 m d^{-1}，與其他兩種氣體交換速率數值接近，表示河流代謝作用對二氧化碳豐度變化影響微小，二氧化碳也具備示蹤之潛力。整體而言，測量河段之能量消散率介於 0.03~0.26 m^2 s^{-3}，氣體交換速率介於 11.3~81.8 m d^{-1}，相較前人研究之大河的氣體交換速率及能量逸散率高，與其他小河系統的氣體交換速率及能量逸散率相當。本研究後續擬至相異水利參數之其他流域，測量氣體交換速率並分析各式水力參數與氣體交換速率

的關係，進而建構臺灣高山小河流域的氣體交換速率模型。

關鍵字:碳源、高山小河、氣體示蹤劑、氣體交換速率

引用資料:

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Exploring the Usefulness of X-Ray Computed Tomography in Lithofacies Characterization

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Abstract

The characterization of lithofacies, identified by their distinct sedimentary attributes, plays a pivotal role in understanding depositional histories. This knowledge is fundamental for reconstructing paleo-environments and may shed new insights into resource exploration and geohazard assessment. Classical techniques such as core description, grain size analysis, and well logging, while useful, face challenges including observer bias, time-consuming methods, and limitations in subsurface examination. X-ray Computed Tomography (X-ray CT) emerges as a promising add-on, offering rapid, non-destructive, and high-resolution three-dimensional visualizations alongside qualitative and quantitative analyses. Our study leverages X-ray CT to investigate five sediment cores from the Dapping Bay area in southwestern Taiwan, showcasing diverse sedimentary features. We aimed to assess X-ray CT's effectiveness in differentiating lithofacies by implementing a comprehensive three-step methodology: (1) systematic scanning of cores, (2) extraction of CT-derived intensity and statistical data, and (3) comparison of core lithofacies with contemporary depositional conditions. We utilized three CT-derived parameters—mean intensity, intensity range, and standard deviation—to identify trends and variations indicative of different lithofacies. Notably, the analysis revealed the influence of core cracks and variations in grain size on mean intensity profiles, while the presence of inclined layers and varying density materials, such as shells and charcoals, were marked by peaks in the range and standard deviation parameters. This study underscores X-ray CT's capability in quantitatively distinguishing lithofacies for revealing specific sedimentary processes, potentially setting a precedent for future lithofacies analysis in similar sedimentary environments and extending the temporal scope by applying it to long cores.

Keywords: X-ray computed tomography, lithofacies, core analysis, event layer

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Deciphering Event Deposit Provenance and Mechanisms along the Japan Trench with Chemical Event-Stratigraphic Correlation

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Abstract

Megathrust earthquakes in subduction zones, such as the AD 2011 Tohoku-oki earthquake, are typically of large magnitude and significantly impact human society. Understanding the characteristics of event deposits formed after these earthquakes is crucial for paleoseismology and seismic hazard assessment. These event deposits enable extending earthquake records through their spatiotemporal distribution, requiring precise distinction and correlation. International Ocean Discovery Program (IODP Expedition 386 collected over 800 meters of sediment cores from 11 trench-fill basins along the Japan Trench. By applying X-ray Fluorescence Core Scanning (XRF-CS with multivariate statistical techniques, such as Principal Component Analysis (PCA and Cluster Analysis (CA, the efficient and non-destructive high-resolution method, the chemical characteristics of these event deposits could be objectively differentiated and correlated. Event deposits at sites M0083 and M0089 in the same basin can be correlated, including those triggered by the AD 1454 Kyotoku and AD 869 Jogan earthquakes. The consistent chemical event-stratigraphic sequences were also observed in adjacent basins at sites M0089 and M0090, validating the effectiveness of our chemical-based event correlation. The ongoing discussion aims to unravel spatiotemporal provenance changes and possible flow mechanisms of event deposits. Cores from M0083 at the depocenter and M0089 at the basin slope reveal notable differences in turbidite thickness and structure, which will be investigated to discern the flow and deposition mechanisms of turbidity currents. Our findings provide valuable insights into provenance changes and the spatiotemporal distribution of event deposits along the Japan Trench. Moreover, our methodology promises to inform future

sampling strategies based on chemostratigraphy. It also presents potential applications in other research requiring event-stratigraphic correlation.

Keywords: XRF Core Scanning, Multivariate Statistics, Event-Stratigraphic Correlation, Japan Trench, Submarine Paleoseismology

Chinese Title: 利用化學事件地層對比解讀日本海溝的事件沉積物來源與機制

Chinese keywords: XRF 岩心掃描、多變量統計、事件地層對比、日本海溝、海底古地震學

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運用流槽實驗建立淺層土壤崩塌閾值模型

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摘要

臺灣受到活躍的板塊作用影響，地質狀態脆弱，且位處於季風氣候帶，颱風等豪雨事件頻繁，使得坡地崩塌之災害事件頻傳。隨著氣候變遷所導致之極端氣候日漸加劇，崩塌的發生頻率以及規模都將隨之增加。因此，相關的防災、減災、及預警之研究顯得更加重要。

在過往的研究中，對於坡地崩塌的預警，主要關注在降水與崩塌間的相關性。這些研究通常是以降水強度、降水延時、總降水量等因子，建立相關的閾值，例如：降水強度－降水延時閾值。在地質特性方面，前人研究有透過監測地電阻值觀察崩塌前後土壤含水量的變化，或以土壤孔隙水壓力、土吸力等性質變化探討崩塌發生的機制。然而，大多數的研究都為仰賴降水的被動研究，存在變因控制上的問題。另外，受限於監測設備的架設成本，部分研究無法獲得大量數據。若是在實驗室中進行模擬實驗，則可以通過控制坡度、土壤性質、降水強度等變因來主動獲取研究數據，更能夠釐清崩塌發生的機制。

本研究在實驗室中架設了流槽坡地模型，尺寸為長 180cm、寬 60cm、高 60cm，土壤深度為 40cm。主要坡度設定為 35°、40°、45°，並以浮子式流量計控制水流量，進而改變模擬的降水強度，降水強度設定為 60mm/h、80mm/h、100mm/h，試圖以實驗模擬的方式觀察崩塌的發生。在模擬過程中，土壤層中孔隙水壓的變化可以透過埋藏於距土壤表面 10－30 公分深的振弦式水壓計來測量。最後，藉由降水的控制以及不同坡度的模擬，建立崩塌發生的降水強度－降水延時之閾值，以期建立一針對淺層土壤崩塌的預警模型。

Studying field-scale dam breach due to overtopping by using seismic signals

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Abstract

A dam is the natural damming of a river by the geohazards, such as landslides and debris flows. When the dam materials are eroded or washed away due to scour, erosion, and/or an increasing in water level of dam lake, leading dam breach and catastrophic outburst flooding, which affect the downstream area. Therefore, real-time monitoring of dam failure would facilitate relevant early warning message for the impending floods. This study has conducted a series of field-scale dam breach experiments, and installed seismic instruments on both sides of the dam (left and right banks) to record three-components seismic signals and analyze the dam breach process due to overtopping failure. Two types of experiments with distinct compaction (compacted (CP) and non-compacted (NCP)) were conducted, and were further divided into single dam (Dam-I), and single dam plus spur dike (Dam-II). Aforementioned experiment setting can significantly affect the dam breach process and the hydraulic characteristics (e.g., surface flow velocity and discharge) during breaching. Based on time-lapse morphological changes of dam, breach stages are categorized into four stages: retrogressive erosion (S1), vertical cutting (S2), lateral widening (S3), and stable stages (S4). This study first computed the power spectral

density (PSD) of breaching seismic signals and further investigated the relations between PSD and flow measurements. In case of CP experiments, a clear seismic PSD increase can be observed during stages of S2-S3. The PSD power recorded by the left bank station is greater than PSD observed in the right bank station. Flow discharge of two experiments of Dam-I and Dam-II exhibits unimodal distribution with peak discharges of 8.14 m^3 and 8.02 m^3 occurred during S3 stage, respectively. In contrast to CP, the PSD of NCP experiments resulted bimodal shape of discharges and showed the relatively weaker seismic power. Notably, two significant PSD distribution patterns can be only observed in case of NCP, especially for the signals recorded by right bank stations. First, during the S2 stage, we observed the extension of the PSD power towards the low frequency coinciding with first peak discharge, which may be caused by the sediment transport. The Dam-II in NCP experiment results the largest eroded volume (239 m^3) during breaching, leading the obvious extension pattern of low frequency PSD. Second, during the S4 stage for Dam-I and Dam-II, the changes in flow path conditions possibly caused the dominant frequency shifting to higher frequency. In a case of Dam-II in NCP experiment, there is a significant seismic power difference between right and left stations. A spur dike located at right bank with a distance of about 20 m away from the dam may cause above PSD discrepancies. Finally, we averaged PSD values in the specific frequency ranges to compute the PSD time series, and then compared PSD data with flow and breaching volume measurements to support our observations existed in all experiments. Our results, especially for NCP experiments, not only advance understanding of the

field-scale dam breach process but also can be applied to the monitoring dams formed by landslides in mountain catchment, which would be helpful for early warning of outburst flooding of dam breaching.

Key words : field-scale dam breach experiments, overtopping breach, seismic signals, power spectral density (PSD), outburst flooding, early warning

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嘉義八寶寮潛在大規模崩塌區域邊坡活動性分析

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摘　要

八寶寮潛在大規模崩塌區域位於嘉義縣中埔鄉，於2009年莫拉克颱風期間曾發生過重大的崩塌事件，有較高的機率再次發生崩塌，而導致社會經濟的損失以及人類生命的傷亡。為找出大規模崩塌中活動性較高的區塊，本次研究將使用數位影像相關法(Digital Image Correlation, DIC)針對嘉義八寶寮進行邊坡地表位移分析，以瞭解此區域2017年至2020年間之邊坡塊體活動性。考量大規模崩塌以最極端的方式整體邊坡於一瞬間發生破壞的機率較低，故有必要再將邊坡進行分區分塊，分別瞭解每一個崩塌區塊的活動性。本研究使用數位影像相關法所得到的邊坡地表位移，再配合地形高線等資料，從整個大規模崩塌區域中，圈繪出活動性較高的小區塊。為討論不同時期邊坡活動性變化，會將不同時期的分析結果，進行相互對比。由研究結果可得知，在2017年、2019年以及2020年，具有較高活動性的區塊位置大致相同，除此之外，影響邊坡活動性的因素，可能與發生於研究區附近的地震有關。藉由數位影像相關法可分析出邊坡地表的位移，進而找出活動性較高的區塊，可提供後續進行防災治理參考。

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發展多相流底泥擴散模式以探討海底山崩碎屑之力學特性

葉宸豪[1]、張哲瀚[1]、吳祚任[2]、林殿順[2]
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摘　要

大規模地震事件發生時，海底盆地之表面沉積物可能發生懸浮現象，Ikehara (Ikehara at.el, 2020) 於研究中表明，過去三場大規模地震中(2011 Tohoku-oki ,1968 Tokachi-oki ,1896 Sanriku-oki)，海底盆地表面沉積物有再懸浮之情況，於2011 Tohoku地震發生後，除引發海嘯外，於三陸斜坡及日本海溝之海床上，有異常高度混濁之現象。Ashi (Ashi et.al , 2014) 提到2004南亞地震發生後，南海增積斜坡上處之盆地中，觀測到極高混濁度之懸浮沉積物。對於此現象沉降後所成岩之岩石型態是否為均質岩成岩之機制受討論且具有爭議之複雜問題，本研究以Splpash3Dplash3D多項流數值模式進行海底山崩懸浮過程模擬，探討深海均質岩事件層沉降機制及情境式分析。本文利用Splpash3D本身具流體體積法(VOF)進行泥沙、水與空氣等多相流運動模擬。為詳實描述沉積物懸浮過程中所呈現之擴散現象，本研究全新發展底泥擴散模式。此外，為描述海盆沉積物所呈現之非牛頓流體特性，本研究進一步結合不連續雙黏性流模型(Discontinuous Bi-viscous Model)，以模擬海盆沉積物受地震加速度力後所呈現之懸浮與沉積之過程。整體數值模式過程包含求解VOF方程式、Navier-Sto kes方程式，並利用Two-Step Projection Method，結合Solenoidal Condition 求解多項流之Dynamic及Kinematic過程。並於Predictor step中，導入新發展之底泥擴散模式與DBM模式。

本研究將所開發之底泥擴散模式進行模式驗證。驗證案例包括海底泥流型山崩模擬，以及受海嘯影響之海堤後沖刷模擬。本研究預期論證深海均質事件層之假說，並進一步探討其特徵與可能成因。目前成功發展底泥擴散模式，其餘細節包括材料之擴散現象、模式設置等，將於海報呈現。

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氣候變遷情境颱風事件誘發山崩風險評估：以曾文水庫集水區為例

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摘　要

受氣候變遷影響，極端降水的強度可能發生改變，例如不同的全球暖化增溫情境下，颱風事件的總降雨量與最大時雨量可能超越歷史紀錄，因此如果能夠透過模型預先掌握不同降雨事件的基礎潛感值，便可在氣候風險分析中做為脆弱度使用，而危害度便為未來情境資料下的總降雨量與最大時雨量的變化，最後暴露度所使用的資料為人口密度。當相關單位能藉由三項指標整合而成的山崩風險，了解到該地區因為氣候變遷所影響的規模與大致分布，便能及早規劃相應的調適行動，以降低災害所帶來的影響與損失。

本研究的研究區域為曾文水庫集水區，首先運用隨機森林分類法，將四個歷史事件型山崩目錄（賀伯颱風、海棠颱風、卡玫基颱風、莫拉克颱風）分別整理成訓練資料（賀伯颱風、海棠颱風、卡玫基颱風）與驗證資料（莫拉克颱風），蒐集並篩選出對山崩影響較大的因子資料，初步分析成果發現以坡度、坡向、平面曲率、高程、NDVI、河距、道路距、相對坡高等因子，為最主要的山崩關鍵潛感因子。誘發因子為造成山崩的主要因素，本研究進一步以降雨為驅動因子，當降雨開始時，雨水會滲漏至地層中，造成孔隙水壓升高，有效應力降低，誘使山崩發生。參考TCCIP的國家氣候變遷情境，以全球暖化增溫情境的颱風事件資料為基礎，分析颱風事件的降雨量，便能推估未來降雨的特徵變化，並與歷史颱風事件比較，了解不同事件對山崩的影響程度。本研究選用總雨量與最大時雨量兩種誘發因子，整合潛感因子建立評估模型。透過前述建模以作為計算脆弱度的工具，再利用驗證資料放入模型中，檢驗所建立模型是否能成功預測事件型山崩，目前成果以莫拉克事件驗證的成功率為0.81，顯示模型有能力預測颱風事件所誘發的山崩。危害度使用降雨因子的變化率，利用TCCIP所提供的AR5不同增溫情境下，動力降尺度產生的颱風時雨量資料，計算出事件總雨量與最大時雨量呈現增加趨勢。暴露度的指標使用人口密度，資料取用內政部國土資訊系統提供的資料，為村里等級的人口密度。目前研究中三種指標已整理完成，預期在氣候變遷的影響下，曾文水庫集水區的山崩風險相較於基期會有增加趨勢，並會因為增溫幅度增加，而使崩塌風險值上升。

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2023年2月6日規模7.8土耳其-敘利亞地震前之電離層異常現象

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摘　要

在2023年2月6日於土耳其東南方與敘利亞的交界處（北緯37.2°，東經37.0°，深度10.0公里）發生了規模7.8的主震及許多強烈的餘震。透過全球電離層圖(Global Ionosphere Map, GIM)全電子含量 (Total Electron Content, TEC)進行時間及空間分析，即觀測 TEC 於經緯度上異常的分布情形，而 GIM 共計 5183 (73x71) 個格點中，在土敘地震發生之前第16天(1月21日)以及第1~0天(2月5日~2月6日) TEC 的異常增加現象在震央上空附近出現，說明地震電離層前兆的存在與未來之發展性。再來也將會使用福衛五號上的科學酬載先進電離層探測器(Advanced Ionospheric Probe, AIP)，量測離子密度及離子速度進行後續研究。

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A fast unsupervised deep learning algorithm using seismic records of a single station for roadside rockfall recognition

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Abstract

The steep terrain in mountainous areas poses a significant threat to people's safety due to frequent geological hazards (e.g., rockfall and slope collapse, making effective management, monitoring, and timely issuance of alerts and warnings crucial for highway authorities. Our study focuses on roadside rockfall incidents, particularly along the 49.7 km mark of the Beiheng Highway in the Fuxing District, Taoyuan City (Figure 1. Over the past year, frequent rockfall events have led to slope collapse, necessitating repeated road closures and traffic restrictions, causing inconvenience to commuters between Baling and Mingchi. To ensure the safety of road users, the development of an automated and reliable rockfall monitoring system is imperative. This study outlines the necessity and proposed development of such a system, which aims to enhance safety measures and mitigate disruptions caused by rockfall incidents along the designated highway section. In the past, the rainfall thresholds have been implemented to make alarm of possible rockfall occurrence. Recently, machine learning using seismic signals has been applied to detect rockfall events and monitor its activity. However, supervised machine learning algorithms have relied on predefined labels, and the limited accumulation of data makes predicting model reliability challenging. The time-consuming model training can limit the practical application of the above models. In response to both challenges mentioned above, we first selected the roadside slope with relatively high activity of rockfalls and earthquakes as the study site and installed a seismic station on the crest of the slope (rectangle; Figure 1. Our study adopted an unsupervised machine learning framework to reveal patterns from unlabeled data and then cluster seismic signals in continuous seismic records in the single three-component seismic station. Our approach combines a deep scattering network, features extraction, and features cluster to understand different source types existed in signal segments. To illustrate the framework, our study employs deep scattering networks to perform convolution and pooling for multi-scale feature extraction from three-axis seismic time-series data. A scattering network layer is constructed to generate scattering coefficients (Figure 2, and Figure 3 shows the multi-scale wavelet coefficients both in time and frequency domain. Aforementioned scattering network architecture facilitates effective feature extraction and representation learning from seismic data, contributing to enhanced understanding and analysis of seismic events. For a purpose of seismic source-type grouping, this research first employs Principal Component Analysis (PCA

for dominant feature extraction (Figure 4. Subsequently, the major eigenvalues are mapped to lower-dimensional space. Finally, an unsupervised learning algorithm, the K-means model, is then utilized for clustering analysis (Figure 5. This methodology facilitates effective dimensionality reduction and cluster identification, providing insights into the underlying patterns within the dataset. We demonstrate the group categories belonging to rockfall events with in-situ data time-lapse images and videos. An approach proposed in this study could achieve rapid model training for building on-site rockfall warning systems using only single-station seismic records. Our high capability recognition model of rockfall events is ready to be implemented globally with high rockfall activity.

Keywords: unsupervised machine learning, deep scattering network, rockfall, seismic records, on-site early warning.

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台灣北部外海基隆海底火山區域之高解析地層構造研究

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摘要

菲律賓海板塊在台灣東北部向西北方向隱沒至歐亞板塊的下面，因為南沖繩海槽張裂逐漸由東北向西南移動，因此，在台灣東北處，台灣造山運動從早期到晚期，經由地殼抬升轉變為塌陷。台灣東北部正處於後碰撞時期。因為南沖繩海槽張裂，所以在台灣東北外海有多東北—西南走向的正斷層，使得台灣東北部外海多呈現半地塹和地塹的地形樣貌，在基隆外海底，有錐狀突起的構造，根據資料，熱液活動旺盛，微震活動頻繁，推測此海底錐狀體是基隆海底火山，其雜亂尖刺狀的頂部形成原因是因為基隆政府為了避免船隻的意外再度發生，在 1989 年將其炸低，此構造附近可發現許多噴氣，推測這些氣體可能會沿著正斷層向上移棲，近年因為環保意識抬頭，各國極力推廣再生能源，如地熱能源，對於地熱能原來說噴氣的位置分布就很重要，又因為地震或火山活動如果太靠近陸地，可能會產生災難性海嘯，基隆海底火山又鄰近台北，台北是台灣的大都市，又有核能發電

廠，因此本研究使用新海研二號 0082-KL1、0093 的水深、電火花反射震測、船載底質剖面和水下探測聲納系統的資料，在基隆火山附近收集了 15 條 24 頻道電火花反射震測剖面和 15 條與電火花反射震測剖面重疊的底質剖面，來探討基隆海底火山附近的噴氣分布和基隆海底火山的基盤分布。首先，本研究用電火花反射震測剖面來看台灣東北外海的深部構造，例如:斷層、火山基盤和地層...等，接著，用船載底質剖面去看電火花反射震測剖面無法看到的淺部構造，來去推測出哪處可能會有噴氣，最後，利用水下探測聲納系統的資料來去驗證是否真的有噴氣。

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947南漢珠江口海嘯之模擬與還原

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摘 要

近期，中國匡耀求教授及其團隊於中國廣東省廣州市南越王宮博物館考古地層中發現，於南漢中期之地層中出現大量海相生物碎屑。該遺跡明確的指出南漢中期該場址大規模海水入侵。此外，該研究團隊亦發現，於《南漢金石記》（清，吳蘭修） 記載「劫石成灰兮，丘陵潛燬。大海為田兮，人倫斯改」，以及《雲門匡真師禪錄》（宋，守堅）中記載「波濤去速，回眸而已逐東流，伏願，鳳曆長春，善皇風於拂石之劫。」由此可判斷該海水入侵為大規模海嘯事件。透過大量出土遺跡及文獻記載，該團隊推測，約於西元947年秋天，於廣州珠江口一帶曾發生一場大規模海嘯事件。

本文透過COMCOT海嘯模式及IIA(Impact Intensity Analysis)法，分析與模擬該事件可能之海嘯源。並還原947年南中國海之海嘯事件之情境。分析方法為透過IIA分析法回推可能之海嘯源，再由COMCOT海嘯模式進行模擬。IIA之分析結果顯示，可能之海嘯源分為近源及遠域海嘯。其中近源海嘯位於陸棚斜坡邊緣，由於該場海嘯記載未提及地震發生，因此可能為山崩海嘯。為此本研究以Watts山崩海嘯模式進行分析。在遠域海嘯部分，則主要分布於南中國海周邊之板塊隱沒帶，尤其是馬尼拉海溝為主要海嘯發源處。

運用多頻道反射震測資料分析

2018 年花蓮地震的海域斷層構造

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摘 要

2018 年 2 月 6 日 23 時 50 分一場芮氏規模 6.2 的地震襲擊花蓮市，震央位於花蓮縣政府東北方 16.5 公里的海域，最大震度達到七級。由於此次震源深度只有 6.3 公里，因此允許我們使用多頻道反射震測資料來探討花蓮外海的斷層構造。本研究分析 2023 年 10 月 NOR2-0113 航次在花蓮外海採集的 37 條多頻道反射震測剖面資料，測線全長約 800 公里，其中地震震源區測線最密集間距不到 1 公里。我們將探討並重建 2018 花蓮地震震源區的地層構造、判別斷層的位置、解釋斷層的位移方向，並討論海域構造受到 2018 花蓮地震的影響。我們也將對本研究建立的花蓮外海沉積地層剖面與 2018 花蓮地震餘震分布以及靠近震源區的花蓮米崙斷層進行比較與分析。

關鍵字: 米崙斷層、多頻道震測、花蓮外海、地層剖面、2018 年花蓮地震
Key words: Milun Fault, Multi-Channel Seismic, Offshore Hualien, Stratigraphic section, 2018 Hualien earthquake

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早更新世南太平洋高緯度浮游有孔蟲群集分析及古海洋學上的意義

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摘要

前人研究認為現代的西太平洋暖池主要受到來自南太平洋中高緯度的帶有冷卻訊號的中層水進入至低緯度，並於早更新世開始發育，但是目前仍缺乏南太平洋高緯度地區早更新世時間段落的紀錄。本研究利用 IODP 383 航次的 U1541 站位(54°12.756′S, 125°25.540′W，水深 3604 公尺)的海洋沉積物岩芯進行浮游有孔蟲群集豐度分析，探討南太平洋高緯度地區古海洋環境之變化與低緯度之間的連結。浮游有孔蟲群集豐度分析顯示有 7 個種屬，最少豐度大於 3%，豐度由高至少為 *Neogloboquadrina pachyderma* (39.6% – 96.9%)、*Globorotalia spp.* (0.6 – 55.3%)、*Globigerina bulloides* (0% – 22.4%)。其中 *N. pachyderma* 有著形態上的差異，臍面有 4 個房室(a 型態)或 4.5-5 個房室(b 型態)的差異，由前人研究得知 a 型態多生長在較冷的環境中，b 型態則是多生長在較溫暖的環境中。a 型態的相對豐度在 2.4 – 2.1 Ma 期間下降，在 2.1 – 1.8 Ma 期間維持在較低的比例，在~1.8 Ma 之後緩慢增加。相反地，b 型態在 2.1-1.8Ma 期間保持在較高比例，並在~1.8 Ma 之後下降，該結果指示在 2.1 – 1.8 Ma 的古海表溫較為溫暖。本研究也進行浮游有孔蟲數量和地軸傾角(obliquity)之間的相位關係(phase relationship)，兩者之間的相干性(coherency)在~2.1 Ma 後上升。浮游有孔蟲群集分析和與地軸傾角之間的相位關係變化的結果可能意味著 2.1 – 1.8 Ma 期間南太平洋高緯度出現類似正相位(positive phase)的南極震盪（southern annular mode，SAM）狀態。在現代海洋觀測中，南極震盪進入正相位後，西風帶(Werterlies)收縮、增強並向南移動，隨之副熱帶鋒(Subtropical Front)向南移，U1541 站位的海表面溫度因而升高，亞南極模態水(Subantarctic Mode Water)的產生量也會增高，並且輸送更多的冷水從高緯度地區經由副熱帶環流進入到低緯度。該海洋狀態可能也發生於 2.1 – 1.8 Ma 期間，較多的冷水由高緯度被輸送到低緯度，因而暖池開始發育。

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彰雲沙脊之地層層序及構造演變研究

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摘　要

潮汐沙脊是現代陸架中常見的地形特徵，是為海岸表層沉積，主要透過潮汐、潮流影響，使沉積物堆積形成現今的沙脊。台灣地處於新生代弧陸碰撞造山帶，是高侵蝕速率與高沉積速率的環境，地層受到造山帶的壓力擠壓以及沉積物的重力堆積影響下形成前陸盆地，後期造山運動趨緩穩定後，沉積物往大陸邊緣推進，將前陸盆地填滿變成淺水環境。根據前人研究古環境與古地形的重建，台灣的構造活動非常的劇烈，不管是沉積或是侵蝕速率都非常快速且複雜，其中最近代的一次大事件是末次冰期，全球在末次冰期間海平面下降了約120 公尺，導致當時的環境為侵蝕環境。末次冰期以後海水位開始上升，台灣西部山脈前緣低海拔的盆地大多都受到海水的侵入而開始變成淺水環境開始沉積。

本研究利用電火花反射震測剖面以及底質剖面來更好的了解當時的淺水環境的變化。結果顯示垂直海岸線的測線可以清楚的看到前陸基底不整合面，由於沉積物來源於河流出海口，因此沉積物的厚度往向海處變薄，由剖面上也可以看到不整合面的連續性停在定義上的前陸凸起。剖面中相對淺部的不整合面為末次冰期間所形成的，震測剖面的特徵有被侵蝕過的強反射，隨著海平面的上升，持續堆積會看到低水位時期、快速海進、以及高水位時期的產物。在底質剖面的部分可以清楚看到沉積物有不同的沉積方向，由此探討沉積物運輸的過程。

研究結果顯示根據震測剖面中的層序地層、震測相來看可以辨認出前陸不整合面，末次冰期不整合面、快速海進時期、最大海漫面以及高水位時期。本研究利用等時面去做網格化發現從末次冰期到海進以及最大海漫面時期來看，推測當時的海進是由北開始進入，由沉積物的厚度來看可以發現當時最後的區域在濁水溪出海口附近，隨著海進開始有潮汐流發生，沉積物被潮流運輸開始相東北向移動。

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美岸高區的構造及成因

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摘　要

呂宋島位於歐亞板塊向菲律賓海板塊隱沒的聚合帶上，歐亞板塊沿著馬尼拉海溝隱沒向東隱沒到呂宋島下。呂宋島西側外海有一美岸高區（Vigan High），是一個海底的地形的高區。此高區位於馬尼拉海溝的弧前區，同時也被菲律賓斷層的分支切過。過去的研究(如Pautot and Rangin, 1989）認為美岸高區的成因跟其南邊的Stewart Bank相同，皆為南中國海的中洋脊的海山隱沒而導致隆起的地形，不過，美岸高區之後被菲律賓斷層切過且沿斷層向北移動，因此形成現在觀察到美岸高區在北，Stewart Bank在南的地形。

本研究基於2022年和2023年在勵進號研究船所收集的多頻道海洋反射震測資料、電火花反射震測（Sparker）資料以及水深資料展開。通過分析多頻道海洋反射震測資 料和Sparker資料，我們可以獲得不同解析度和深度的資訊，有助於深入了解地下地質構造。同時，水深資料能提供高解析的海底地形，從而揭示美岸高區的地質特徵及其形成機制。綜合這些資料，我們將能夠深入探討美岸高區及其周邊海域的地質演化過程，為該地區的地質研究提供新的見解和證據。同時也對於該地區的地質災害風險評估和自然資源開發具有重要意義。

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應用於複雜斷層系統之機率式地震危害評估：以花東縱谷為例

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摘　要

本研究旨在驗證機率式地震危害評估中經常使用的地震模型之可信度，並評估它們對危害度所造成的影響。為了驗證模型，此研究將這些方法應用於地震活動頻繁且觀測品質高的臺灣花東縱谷地區。

本研究首先利用Gutenberg-Richter 方法（G-R 法）將在花東縱谷區域所觀測到的地震活動進行回歸，受惠於高品質地震紀錄，它與小到中等規模的觀測結果相當吻合，然而，當此模型應用於大規模的地震時，由於事件數量有限，造成不確定性增加。我們另外使用純特徵地震模型（Pure characteristic earthquake model）預估地震活動，該模型基於構造參數以評估各孕震構造和活動斷層的最大地震發生率，由於大多數構造的回歸週期長於觀測期間，驗證純特徵地震模型的可信度相當困難。本研究也運用Seismic Hazard and Earthquake Rates In Fault Systems（SHERIFS）模型，考慮 G-R 法中的 b 值和孕震構造參數，討論每個斷層的破裂行為。在此模型的結果中，我們獲得與斷層不同距離的觀測結果，此模型在預測孕震構造沿線的地震發生率以及花東縱谷地區的區域地震活動具有良好表現，其通過考慮多重構造破裂與歷史的觀測記錄相符。

最終我們將所有地震模型整合到機率式地震危害評估中，並比較其異同。這項研究的結果對於理解複雜的斷層系統之地震物理、提出地震機率預報，以及提供更準確的地震危害評估參數至關重要。

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On the temporal variations of near-surface seismic structure of Taiwan and its geological inferences

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Abstract

We report on the temporal variations of the near-surface (< 500 m) seismic structure (Vp, Vs, and Vs anisotropy) of Taiwan using the empirical Green's functions of body waves between vertical station pairs at 60 borehole sites. In our previous work, the obtained near-surface anisotropy are categorized into stress-aligned anisotropy (SAA) and orogeny parallel anisotropy (OPA). Since all the major geological units of Taiwan are well sampled by borehole arrays, and drilling data for 52 sites are available, we were able to find that OPA is typically stronger than SAA, SAA strength is generally higher in sedimentary rocks, igneous rocks, and gravel sediments compared to fine-grained sediments, and OPA is more pronounced in foliated metamorphic rocks than in dipping sedimentary strata. In this study, we aim to address the following specific questions with the obtained results: (1) How do the temporal variations of near-surface seismic properties in different geological units of Taiwan correlate with seismic activity or nearby earthquake events? (2) Are there distinct patterns in the temporal variations of anisotropy strength based on the specific geological composition? (3) Do sites characterized by OPA exhibit different temporal variations in response to seismic activity compared to sites dominated by SAA?

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三階段逆推探討中源地震的破裂特徵：以 2021 年 10 月 24 日 M_L 6.5 宜蘭地震為例

Examining the Rupture Features of Intermediate-Depth Earthquakes by a Three-Stage Inversion: A Case Study for the 2021 M_L 6.5 Yilan Earthquake

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摘要

三階段逆推包含遠場 P 波逆推、非負解時間域解迴旋及有限斷層震源模型反演，本研究將此應用於探討 2021 年 10 月 24 日宜蘭 M_L 6.5 地震的破裂特徵。首先，以遠場 P 波逆推得到此地震的震源機制，其深度為 67 公里、地震矩為 1.70×10^{18} Nm 和斷層面解為 62°/19°/114°和 187°/79°/75° (strike/dip/slip)；其次，以非負解時間域解迴旋得到隨測站方位變化的震源時間函數，再輔以破裂方向性分析得到此地震斷層面為 62°/19°/114°，破裂速度 4.58 km/s，破裂長度約 21 公里，破裂方向約北偏東 107°；最後，以震源時間函數進行有限斷層震源模型反演，獲得了斷層面上的滑移分布，可看出此地震主要是由三個子破裂所形成的，整個地震歷時約 4-5 秒，而破裂過程的時間切片更明確顯示這些破裂主要都是沿著斷層走向由左向右破裂，將之投影至地面，也就是朝遠離台灣方向破裂，這大大降低了對台灣的危害。

關鍵詞：遠場 P 波逆推、時間域解迴旋、有限斷層震源模型、震源時間函數、震源機制

Key Words: Teleseismic P-wave inversion, Time-domain deconvolution, Finite-fault source model, Source time function, Focal mechanism

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Earthquake Detection in the Taiwan MiDAS Borehole Seismometer Array

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Abstract

The 2018 Hualien earthquake caused severe damage in the Hualien region, along the Milun fault. Six years after the earthquake, the Milun Fault Drilling and All-inclusive Sensing project (MiDAS) initiated two scientific drillings in the hanging wall (700 m, Hole A) and the foot wall (500 m, Hole B) of the northern Milun fault. It successfully drilled through the Milun fault in Hole A and got a 50-m thick fault core. After drilling, the MiDAS project deployed an optical-fiber cable and borehole seismometer arrays in both holes to monitor seismicity on the Milun fault.

In this study, we use data recorded by the borehole seismometer arrays to establish an earthquake catalog, aiming to gain insight into the microseismicity on the Milun Fault. We apply two methods for seismic event picking; one is the regular manual picking method; another is a machine learning phase picking technique, RED-PAN (Liao et al., 2022). Our study period is from March 16 to April 15, 2023 (31 days). In the manually picking results, we identify 621 earthquakes. Among them, 45 microseismic events are strongly related to the Milun fault, which ts-tp time less than 1 second. On the other hand, the RED-PAN has been proven to be most efficient in processing the MiDAS data with a high-pass filter of 10Hz and a prediction time window of 30 seconds. The RED-PAN detects 830 events based on this configuration. 77% detections are verified as earthquakes. However, our results show that the RED-PAN is not familiar to detect microevents just near the sensors. Only 10 events with a ts-tp time less than 1 second are detected. The precision of 22% is relatively low compared to it of the detection for entire events. Our next step is to retrain the model of RED-PAN and increase its detection ability for nearby events. We expect that an updated RED-PAN is able to operate independently in event picking process and save workforce. It would be a huge benefit for further seismological studies in the MiDAS project.

Key words

microseismic, Milun fault, borehole seismometer, machine learning model

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Earthquake monitoring in a field laboratory in northern Hualien, Taiwan

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Abstract

Seismicity in northern Hualien is relatively high compared to it in other regions in Taiwan, due to the area locates on a collision boundary between the Eurasia and Philippine Sea plates, and the Ryukyu subduction zone nearby. The tectonic environment in this area is not clear and has been debated. Magnitude of earthquakes occurred in this area distributes in a wide range from M1 to 8. The distribution of earthquakes is also wide from near surface to 150 km at depth. Due to diversity of earthquakes in size and depth, the area in northern Hualien may be the best location for seismicity activity study. To monitor seismicity in this area, we established a field laboratory near the Heping village in 2020. It has operated a broadband seismometer placed in a borehole at a depth of 100 meters, an acceleration seismometer, and a velocity 3-component geophone on the surface. Combining borehole seismometers deployed by the Central Weather Administrator (CWA), is able to increase capability of earthquake detection, especially for microearthquakes. In the first stage of this study, we calibrate the horizontal azimuth of the borehole seismometer in the field laboratory by using long-period waveforms from the 2021, Qinghai earthquake in China. The corrected angle is 339.11° counterclockwise. In the second stage, we pick up 2026 events manually from the continuous records of the borehole seismometer in the laboratory during two periods: October to November 2020 as well as, October to December 2022. Among them, we identify 217 events that are not listed in the CWA earthquake catalog. We successfully located 125 events by using the 3-D velocity model in Taiwan. These events are clustered to the north of the laboratory, which might be related to interactions of colliding and subducting behaviors. In the future, we will focus on determining the focal mechanisms and other source parameters (e.g., magnitude and stress drop) to understand stress condition of this complex tectonic region.

Keyword: Borehole seismometer, Earthquake location

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Exploring Velocity Pulses Generation through 3D Ground Motion Modeling in the 2016 Meinong, Taiwan Earthquake

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Abstract

Recent studies have shown that velocity pulse waveforms are commonly observed during earthquakes, particularly in areas where the fault rupture exhibits directivity, advancing toward a specific direction and underscoring the influence of rupture directivity on seismic wave propagation. Waveforms resembling pulses are recognized for inducing more significant ground shaking and severe damage to structures, marked by heightened amplitude and longer durations. For example, the 2016 Meinong earthquake in Taiwan is notably characterized by its unique velocity pulse waveforms. This phenomenon led to more severe casualties and structural collapses in Tainan compared to Kaohsiung. Lee et al. (2016) conducted a joint source inversion of the Meinong, Taiwan, earthquake to elucidate the coseismic slip distribution and pinpoint factors responsible for larger ground motions in southwestern Taiwan. In this study, we investigate the generation of the velocity pulse through numerical simulation of the Meinong earthquake, leveraging the finite-fault model established by Lee et al. (2016). We extract the kinematic source parameters of the finite-fault model from Lee et al. (2016) and introduce perturbations to investigate the impact of various parameters on the generation of pulse wave signals, including the size of asperities, rupture velocity, and the source time functions of subfaults. Subsequently, we simulate seismic wave propagation using the 3D finite-difference method (FDM), considering the impact of different 3D velocity models on wave propagation. We calculate the ground motion at the seismic bedrock and on the ground surface, then compare these synthetic ground motions with empirical data and recent-develop ground motion models (GMM). This comparative analysis assists in identifying the factors that contribute to the generation of velocity pulses, thereby improving the accuracy and reliability of simulations for use in earthquake engineering applications.

Keywords: Meinong earthquake, Finite-difference method, velocity pulse

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嘉義地區之場址特性探討

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摘　要

吳澄峰(2012)曾在嘉義地區46個場址施行微地動陣列量測，探討其淺層S波速度構造(約0~1500m)，本研究主要利用赫氏方法及此速度構造計算這些測點地表相對於不同深度之理論轉換函數(包含6個不同深度層及5個不同V_S速度層)，並估算這些測站地底下不同地層之第一共振主頻及其所對應之放大倍率值，進而綜合探討嘉義地區之場址特性。

根據這46個陣列場址利用differential方法逆推所得之S波速度構造，本研究估算這些測點地表相對於6個深度層(即50、100、200、400、700及1000 m)之第一共振主頻，其分布範圍分別為1.27~2.73 Hz、0.76~1.60 Hz、0.52~0.93 Hz、0.37~0.62 Hz、0.25~0.48 Hz和0.21~0.42 Hz。隨著深度增加，第一共振主頻逐漸遞減。再者，估算這些測點地表相對於5個V_S速度層(即350、550、750、1000及1500 m/s)的第一共振主頻，其分布範圍分別為0.70~5.24 Hz、0.51~2.58 Hz、0.28~1.13 Hz、0.23~0.71 Hz、0.19~0.51 Hz。隨著速度層之V_S值增加，第一共振主頻逐漸遞減。兩者之第一主頻高區皆位於東邊(DIL、YIR附近)，而第一主頻低區則位於西邊之嘉南平原(WET、KLU附近)，此地區之沖積層較厚。

假設嘉義地區之第三紀岩盤的S波速度為1500 m/s，則其上方第四紀沖積層的厚度約為565m (DIL)~1418m (KLU)，第一共振主頻範圍約0.19Hz (KLU)~0.51Hz (YIR)，其中位於東邊之DIL及YIR測點為第一主頻高區，逐漸向西遞減，位於西邊之嘉南平原為第一主頻低區，而此第一主頻所對應之相對放大倍率值約7.53 (TUY)~11.57 (CIS)。

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以微地動陣列與多頻道表面波震測求得 S 波速度構造

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摘　要

對於強地動預估來說，速度構造的準確性會影響其結果的可靠性，由於非侵入性（noninvasive）方法的施測成本低且省時，有許多方法已被廣泛使用。本研究討論微地動量測的空間自相關法(spatial autocorrelation method, SPAC)與多頻道表面波震測法(Multichannel Analysis of Surface Waves, MASW)對於頻散曲線的解析度。先進行頻散曲線的比較後，再使用相同程式進行 S 波速度構造逆推，以比較兩者逆推出的速度構造結果。已有先人研究（Hartzell et al., 2005）表明，同樣使用微地動陣列量測表面波，頻率波數法（f-k method）用於量測有明確震源的微地動效果更加；SPAC 法則對於有各方均勻震源的狀況下解析度更高。MASW 由於其施測方便、資料處理快速等優點，近年來已有實際應用案例，但 MASW 方法，卻對於地層側向變化產生的變數更加敏感（Park et al., 1999）。本研究針對中央氣象署位於臺北、花蓮、臺東的某些 Free-Field 測站進行上述兩種方法測量資料的分析與比較，企圖驗證兩方法是否能在結果上一致或產生互補。

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探討台灣dML校正項與場址參數的相關性

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摘　要

台灣位於菲律賓海板塊和歐亞板塊的交界處，地震活動頻繁，並存在許多活動斷層。芮氏規模是根據地震波紀錄之振幅來計算，因此各測站場址條件的差異會對振幅造成不等的放大效應而影響芮氏規模的計算。為了準確表示地震事件的芮氏規模，利用了從多個測站獲得的平均規模值。dML代表地震事件的規模與各個測站所記錄到的規模之間的差異。對於僅能由位於震央附近的站點記錄到的較小地震，dML校正的應用至關重要。在這種情況下，所有測站可能位於硬岩或軟土上，進而可能導致芮氏規模的低估或高估。本研究旨在探討dML與場址參數之間的相關性，評估dML校正對芮氏規模結果的影響。通過實施dML校正，我們期望為地震目錄的一致性做出貢獻，從而提高地震危害度分析的準確性。

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考慮破裂方向性的強地動模型(GMM)在台灣地震預警系統上的應用

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摘　要

台灣位於地震頻繁的板塊交界處，因此在各種耐震設計或地震災害評估中，需要強地動模型(GMM)來評估各地的地動值大小。另外，區域型地震預警系統會即時地偵測地震活動並發出警報，在較具有破壞力的剪力波到達前，提供人們幾秒鐘的預警時間，藉此降低地震造成的災害和損失。當中大規模的地震發生時，經常伴隨著一些強地動特性，其中在近斷層的區域可能會受到震源破裂方向性影響，造成在破裂方向上的地動值(PGA、PGV)有明顯被放大的現象，若我們在地動預估過程中未加以考慮，則破裂前進方向上的地動值可能會被嚴重低估。本研究將破裂方向性效應加入強地動模型的計算中，使用Chao et al. (2020)提出的強地動模型，以及Chao et al. (2019)採用的方向性函數，對近十年幾個地震矩規模大於5.5的地震進行地動值預估，同時與未考慮破裂方向性的結果做比較。期望可以在台灣地震預警系統中，透過上述考慮了破裂方向性效應的強地動模型進即時地預測地動，達到近即時地決定破裂方向、快速地評估破裂方向上的地動值、提升預估結果的準確性等目標。

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Development of a Ground Motion Model Using XGBoost and Its Implementation in Seismic Hazard Assessment

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Abstract

This study employs the XGBoost model to develop a GMM through Taiwan crustal earthquake observations. We accessed the strong-motion records from the Taiwan Strong-Motion Instrumentation Program (as known as 'TSMIP') network. Because of the dataset imbalance, we implemented the SMOGN method to generate some artificial data for training. As a result, our dataset became more balanced, particularly for larger magnitudes and shorter distances, which enabled the machine to learn the scarce parts better and thus improved the performance of the GMM. We tried to predict strong ground motion in respect of various units, including peak ground acceleration (PGA), peak ground velocity (PGV), and various periods of spectral acceleration (SA). To identify the importance of each feature component, we used the SHAP index to decide which features were included in the model. Furthermore, we also confirmed our model can be applied in a seismic hazard assessment. Our study sheds light on developing GMMs via machine learning, beneficial to subsequent seismic hazard assessment in Taiwan.

【參與學生壁報比賽】

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大台南地區場址效應及其與地質構造之關係

Site effect and its relationship with geological structure in Tainan

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摘要

本研究針對大台南地區，由西至東分別是西部平原、台南台地、大灣低地以及麓山帶進行細部場址效應分析，並探討台南場址效應與地質構造之間的關係。過去台南地區所發生的災害性地震，除了 1946 年的新化地震之外，震央皆未發生在台南之內，但是對台南卻造成程度不一的破壞，像是 2016 年的美濃地震。位於表層的台南層根據前人的研究，厚度在台南台地之上約 16~36 公尺，並向西增厚至安平最深可達 170 公尺。因台南地質條件主要為厚層的現代沉積物，其表現的共振頻率以及放大倍率差異，在震波通過時於不同地點造成不同的影響。當震波的頻率和地區的主頻一致時，所形成的共振使地震的震幅放大，導致破壞程度提高。本研究對大台南地區進行了場址效應的調查，資料使用由 2021 年 2 月 2 日至 2021 年 6 月 15 日，總共 173 個站為期 1~3 個月的環境噪訊(微地動)。主要利用這些資訊進行 HVSR (horizontal-to-vertical spectral ratio)的分析，並以 Kmeans 來進行群集分析。針對長時間(幾日)的資料和短時間(幾個小時)的資料進行比對。由此評估微地動所做的 HVSR 是否會隨時間變化，以及驗證短時長之微地動所做出來的結果是否可信。另外，將這 173 個站所做出來的資料與鄰近不同採樣頻率之強震站進行比較，以確認其結果是否正確。

結果顯示各地區的場址效應與地層地質存在一定的相關性。因整體大台南地區表層包含了大量的沉積物，這大大影響了 HVSR 的表現，可以在各個區域觀察到不同頻率的峰值。台南地區的地層主要包含兩個放大主頻，分別為 0.2 Hz 與 1~3 Hz。其中平原以及大灣低地 0.2Hz 的頻率為當地主頻，而台地及麓山帶則是 1~3Hz 為當地主頻，並且相較於平原區域，台地上的震波放大倍率相對較高。在長時間的分析中發現，部分 HVSR 結果具有雙峰值的測站，在大潮發生的時段會有 0.2Hz 的放大倍率提高的現象。而測量出此結果的測站皆位於沉積厚度相對較厚的西部平原以及大灣低地。而主頻 0.2Hz 對應的建築物自然頻率，對於樓層高度 20 樓以上的建築可能在大潮時期會有更加嚴重的損壞。據統計台南地區樓層高度大於 20 層的大樓目前完工的就有 74 棟。本研究希望藉由了解不同地區的場址特性，得到地震的潛在危險區域，用以加強高樓層的維護作業，避免唯冠大樓的事件再度發生。

關鍵字:
場址效應、單站頻譜比法(HVSR)、微地動、環境噪訊
Site effect, Horizontal to Vertical Spectral Ratio (HVSR), microtremor, ambient noise

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結合密集陣列與遠站的干涉波形探討南台灣噪訊分佈及其應用

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摘 要

在均勻的散射場的假設之下，測站間的長時間的干涉波形可視為經驗格林函數，在台灣，此技術已被廣泛的應用於探討淺層地殼速度構造。然而，若噪訊能量分佈不均勻，則可能會誤判構造速度。過去研究顯示台灣周遭的次生噪訊源(Secondary Microseisms, 2-5 sec)的強度與水深及季風系統有關，而原生噪訊(Primary Microseisms, 6-9 sec)的分佈特性仍未有系統性的調查。因此，所以我們結合台南地區由62個測站組成的密集陣列，以及距離此陣列40-80公里間的寬頻和強震站資料，透過密集陣列與遠站之間的交互相關函數 (Cross-correlation function, CCF)，以及相對應之波束成形(Beamforming)結果來探討噪訊源在南台灣分佈的特性。首先受限於密集列測站的展距，在台南地區波束成形中只能解析短周期的結果，而訊號來源主要來源於台灣西岸沿海，此結果與前人研究相符。再來分析密集陣列與遠站的波束成形，我們發現在長週期6秒到10秒在之間，台東成功地區有一個很強的的噪訊源，顯示噪訊來源不均勻可能會影響噪訊層析成像(Ambient noise tomography)的結果。最後，我們透過模擬波場，以及結合近岸水深資料以及波浪資訊，探討其可能的來源與機制。

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基於SVR模型利用氣象資料預測地表位移及振動

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摘　要

劇烈天氣事件後，是否會改變近地表的地質力學特性？而利用環境數據是否可以有效預測地表位移場的變化？本研究選用背景地震活動不活躍的潮州斷層附近為研究區域，利用15年(西元2004年-西元2020年)的環境資料（包含溫度、降水和風速等的連續資料）和地下水位連續資料，並使用支持向量迴歸（SVR）模型來進行地表位移和振動訊號的預測可能性之評估。

15年的資料集分成75%的訓練資料和25%的測試資料，模型預測之地表位移與觀測相比可得高達0.95的R值，說明SVR模型在長期地表變形預測上的可行性。未來將進行幾個極端天氣事件的短期預測模型之資料收集與測試，並進一步進行異常偵測分析之設計與流程設計。

【學生壁報比賽】參與者於摘要尾端註記

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利用噪訊成像技術反演觀音山地區剪力波速度模型

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摘　要

觀音坑是一個位於林口臺地以北、觀音山以南，在圓頂狀地形構造上的近圓窪地，根據地層學及地質構造上的特徵，觀音坑被解釋為一個坍塌的破火山口模型，其中（a）岩脈入侵、（b）火山爆發與之後的熔岩流作用以及（c）火山侵蝕作用，分別主導了1百萬年前、1百萬年前至34萬年前以及34萬年前至今的地質活動。上述的火山及侵蝕作用形成對應的（a）穹頂狀構造、（b）火山渣錐與熔岩流的結構以及（c）火山錐的塌陷和火山破口。觀音坑因位在穹頂中心包含火山碎屑岩及岩脈，被視為岩漿上流的管道。

本研究將在觀音山地區應用環境噪訊成像技術，首先反演該地區對於各週期基態雷利波的二維相速度模型，進而得到三維剪力波速度模型。我們在觀音山地區佈設了約50個簡易地震儀（SmartSolo）組成的觀測陣列，平均測站間距約0.8公里，並結合Formosa Array的部分測站組成我們的觀測網，使用約兩個月的噪訊紀錄進行分析，首先將兩兩測站對的連續紀錄進行互相關後並疊加，萃取各測站配對之間的基態雷利波格林函數（Green's Function）；接著使用多重濾波法（Multiple Filter Technique）得到週期0.5－6秒間的群速度及相速度的頻散曲線；最後使用快速推進法（Fast Marching Method）計算測站配對之間的波線路徑以建構反演矩陣，並反演得出各週期的基態雷利波二維相速度模型。將各測站對之間量測到的各週期相速度呈現於地圖上做初步分析，可觀察到在週期0.5－1.5秒的基態雷利波相速度於觀音山北側區域較快，其可對應到觀音火山岩層的熔岩流；而在週期2.0－2.5秒的基態雷利波相速度則呈現東側較西側快的現象。

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Probing relation between rainfall pattern and seismic detected water-and-sediment events

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Abstract

Southern Taiwan often experienced abundant monsoon seasons during seasonal transitions, and monsoons and typhoons controlled the rainfall patterns to be complex and varied, resulting the high intensity, prolonged rainfall episode. The aforementioned rainfall characteristics can increase the risk of water-and-sediment-related disasters. To probe deeply the relationship between rainfall patterns and water-and-sediment events (WSEs), this study selected the Putanpunuas River in southern Taiwan as the research site (Fig. 1a). The middle and upper watershed of this site experiences frequent landslides, providing the river with a large amount supply of sediment materials. Indeed, the strong and prolonged precipitation can cause high susceptibility of WSEs in this study area. We deployed micro-seismic monitoring network to observe the seismic signals induced by WSEs. The seismic network comprises one station (BNAR) on the right bank and two stations (BNAL, BNAS) on the left bank downstream of the Putanpunuas River, and an additional station (BNAF) at the confluence of the Putanpunuas River and the Laonong River (Fig. 1c). First, this study manually filtered out 6-hours-length seismic spectrograms which contain the signals associated with WSEs (Fig. 2), and then the average power spectral density (PSD) time series can be computed. Furthermore, the seismic signal characteristic parameters (Table. 1) of WSEs were extracted automatically (Fig. 3). Subsequently, employing various machine learning algorithms (Decision Trees, KNN, K-means, Auto-sklearn) to develop an optimized model for identifying WSEs, classifying different types of events (Fig. 4), such as flooding (FD), debris flooding (DFD) and debris flow (DF), then providing 5-year-length (2019~2023) catalogs of WSEs. Rainfall data including hourly precipitation and LiDAR estimated rainfall are collected from the rain gauge stations nearby study area. Using a certain definition (e.g., 4 mm/hr threshold for picking start time) of rain episodes, we calculated total number of episodes and established a rain episodes catalog. By contrasting the timelines of rain episodes and WSEs, we can infer the primary characteristics of rain episodes associated with different WSEs occurrences. The time intervals between event occurrence and specific time (e.g., starting time) of rainfall episode are extracted based on the catalog in this study (Fig .5). With an available dataset of time intervals, statistical analysis has been adopted to determine the identical

probability distribution, which is useful to predict occurrence probability of events. The results of this study can be applied to predict potential WSEs in Putanpunuas River using rainfall information as input. This can facilitate relevant early warning operations, reducing the societal impact of water-and-sediment disasters.

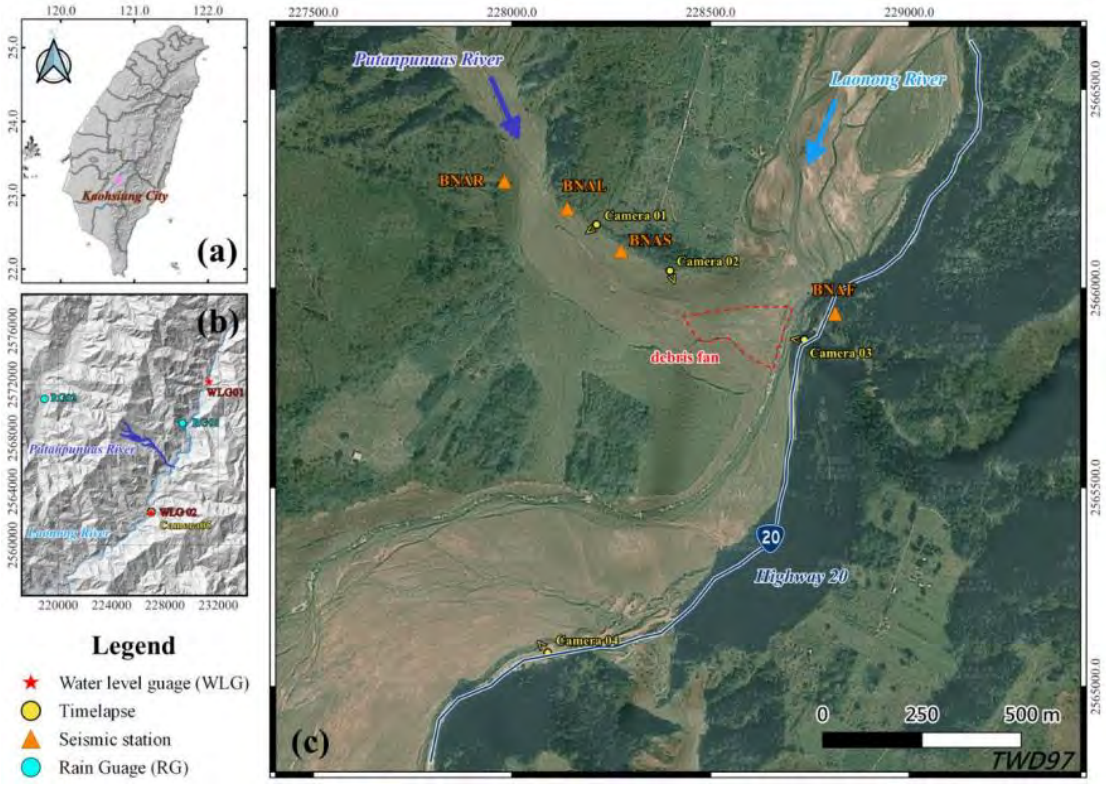


Figure 1. (a) The location of the Putanpunuas River in southern Taiwan. (b) The confluence of the Putanpunuas River with the main stream Laonong River, and the adjacent locations of water level gauges and rainfall stations. (c) The satellite image of the research area includes the positions of Micro-seismic monitoring stations and related instruments.

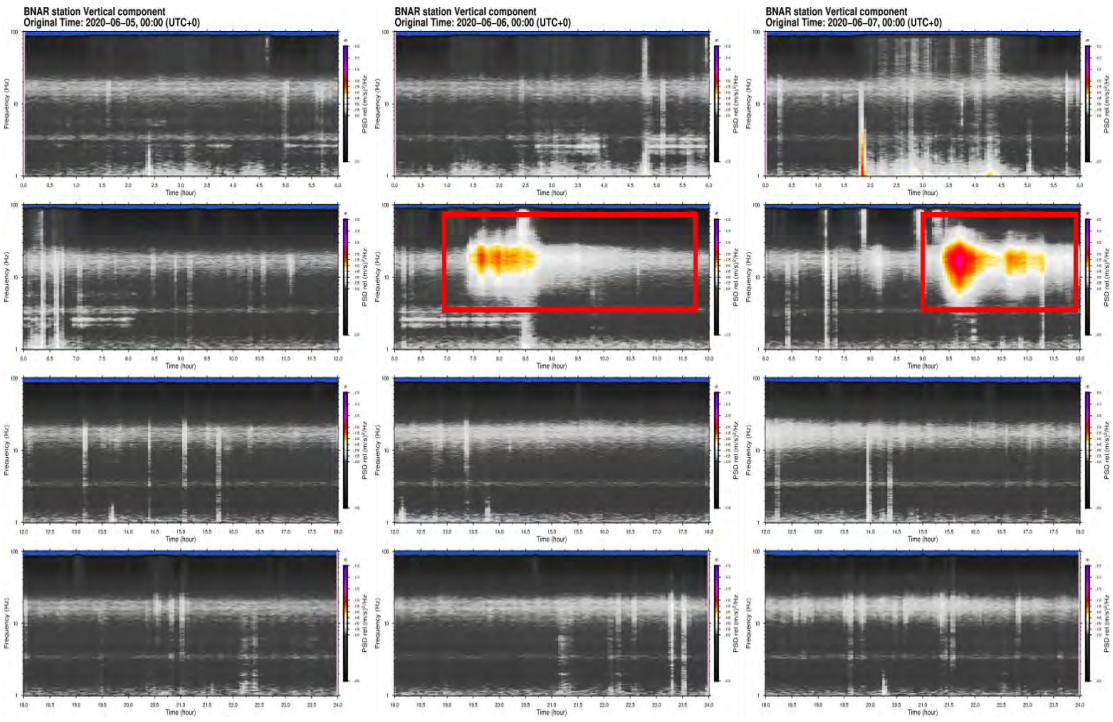


Figure 2. Examples of 6-hour-length spectrograms are associated with background noise (left panel) and WSEs (middle to right panels). Red rectangles highlight the strong seismic power observed in spectrogram, which were manually picked upfrom daily spectrograms during a period of 2019~2023. Color indicates the power spectral density (PSD).

Parameter	Definition
PSD_P	Power spectral density peak vaule
T_P	Power spectral density peak time
T_S	The moment 6 minutes prior to exceeding the STA/LTA threshold of 0.985
T_E	The moment 3 minutes after PSD is below the background level
S_D	The duration of the event, $(T_E - T_S)$
SNR	Signal-to-noise ratio
BGL	Signal background level
S_D	Signal duration
AUP	Area under the PSD curve
SK	Skewness
KT	Kurtosis
UPR	Unit PSD Ratio, (AUP/ S_D)

Table 1. The seismic signal characteristic parameters table.

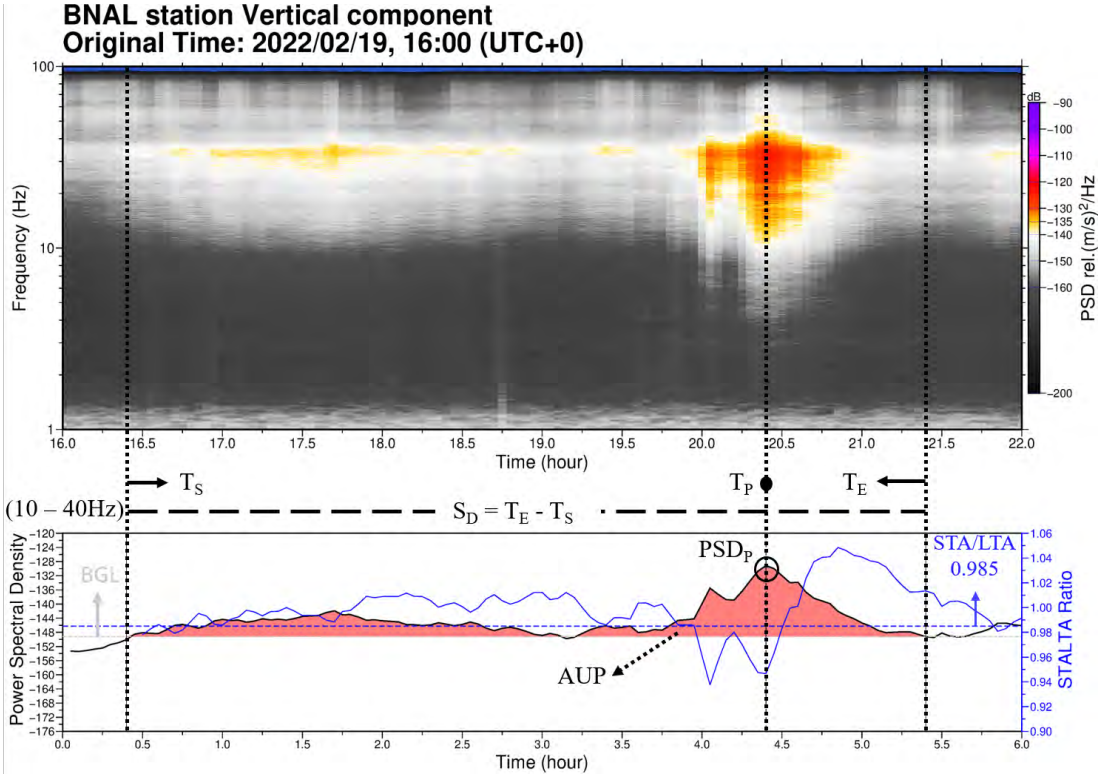
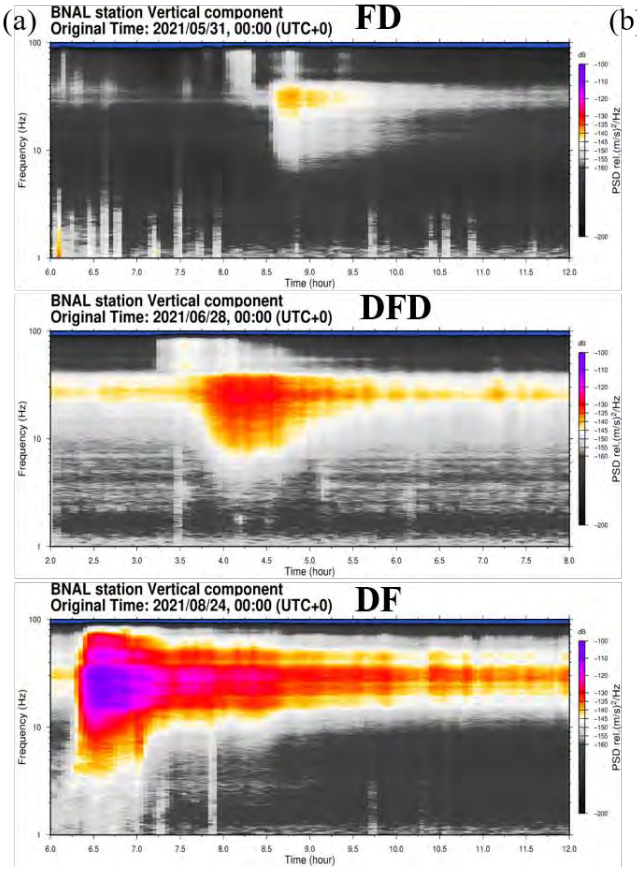


Figure 3. Quantified the average power spectral density values to obtain seismic signal characteristic parameters of water-and-sediment events. PSDp is power spectral density peak value, T here stands for UTC+8, SNR as signal-to-noise ratio, when the PSD after the T_P becomes lower than the background signal level (BGL) marks T_E.

(a)



(b)

Training				
93% Accuracy		Predicted		
		DF	DFD	FD
Actual	DF	14	3	0
	DFD	1	50	1
	FD	0	2	32

Testing				
88% Accuracy		Predicted		
		DF	DFD	FD
Actual	DF	2	0	0
	DFD	2	13	0
	FD	0	1	8

Figure 4. (a) Classifying different types of events with machine learning, Spectrograms of flooding (FD), debris flooding (DFD) and debris flow (DF). (b) Confusion matrix using KNN model for classifying the event source type by using seismic signals (2019~2022) recorded by the BNAL station. A total number of detected WSEs is 129. 80% of these events are used as the training dataset, while the remaining 20% are used as the testing dataset.

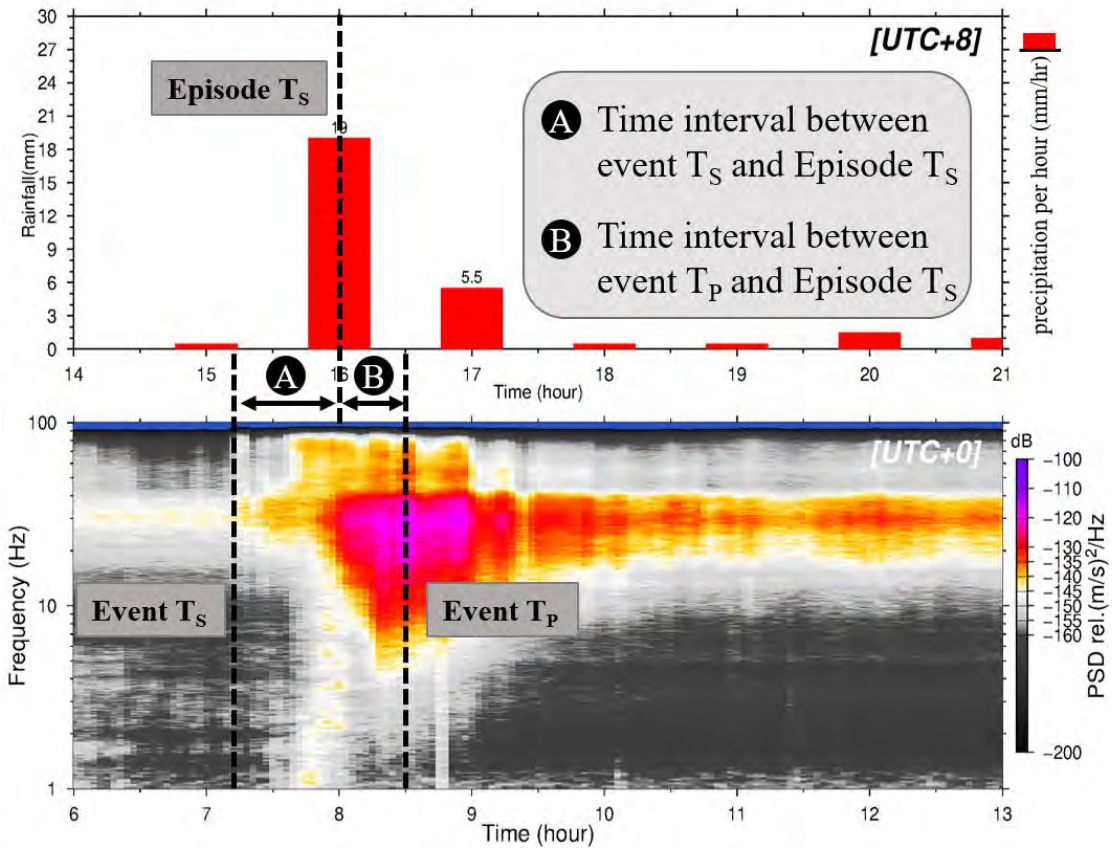


Figure 5. An example shows the procedure to measure the time interval between rainfall episode and WSEs events. Time intervals of A and B were used in study for the statistical analysis in determining the probability distribution..

Key words : Rain Episode, Micro-seismic monitoring network, Putanpunuas River, Water-and-Sediment Events (WSEs), Machine Learning, Spectrograms, Early warning.

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台灣東部花東縱谷微地動資料分析

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摘　要

在2022年9月18日池上地震發生的8天後，我們於花蓮縣玉里鎮長良地區架設了64個微地動測站，所有測站覆蓋區域約35平方公里，西至中央山脈，東至海岸山脈，而南北界則分別為秀姑巒溪以及樂樂溪。其中涵蓋的地質環境由西至東可大致分為崙山層、沖積層和利吉層，同時該區域也涵蓋了中央山脈斷層、玉里斷層破裂帶以及海岸山脈斷層池上段。我們希望藉由微地動的訊號，以頻率波數法(F-K Spectral Analysis method) 搭配相應的陣列，分析位於縱谷平原區域破裂帶周圍速度頻散曲線的樣貌，以及在不同地質條件下，該曲線的變化情形。首先，位於玉里破裂帶處之陣列，最大/小展距為700公尺/25公尺，在以兩倍最大/小展距區間為可信區間(對應頻段為1.5Hz -8Hz)觀測為於其中之速度頻散曲線後發現，速度從約2000m/s降至約450m/s，且在5Hz-10Hz處，存在另一激發態之速度頻散曲線，速度從約1000m/s降至約600m/s。此外再以原先陣列型心為基準，將周遭測站另組成一大展距陣列，用以補強原先小於1.5Hz處解析不佳之頻段，結果顯示在頻段1-2Hz為曲線斜率變化最為劇烈。將此現象輔以單站頻譜比法(horizontal-to-Vertical Spectral Ratio method, HVSR)的結果後，由於與其所呈現之共振主頻相重疊，推測該深度處具有一速度不連續面，而激發態則是由地層中特定深度之高速層導致。同時根據位於中央山脈和和海岸山脈之大展距測站和平原區域測站求得之頻散曲線結果對比，發現在可信範圍(0.2-0.8Hz)中，在同一頻率下，除了在0.2Hz時，中央山脈和平原區域波速相同以外，其餘頻段皆呈現中央山脈波速遠高於其他兩區域波速(差距約為1000m/s-2000m/s)的情形；而平原區域之波速則又高於海岸山脈區域之波速(差距約為500m/s)，目前推測此速度差距是由陣列所在位置深層岩性不同所導致。基於上述所提及的結果以及相關的推測，後續我們將透過聯合逆推的方式，針對HVSR和頻散曲線的結果進行HVINV逆堆，進而求得該區域地層中確切的速度構造，以及速度和岩性的關聯性。

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Probing the SAA Depth Range using ML-measured short-period dispersion

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Abstract

In this study, we aim to explore the depth range of stress-aligned anisotropy (SAA) in Taiwan. Our recent works have shown that the near-surface SAA is consistent with shear-wave splitting studies employing local earthquakes. However, it contrasts with SWS studies using deep phase (SKS) and the shallow crustal Vs anisotropy model derived from noise-derived broad-band (4-20 s) Rayleigh waves. This suggests that SAA is likely confined to the uppermost crust. Despite micro-cracks assumed to be fully closed with increasing ambient stress at depths, the depth range of the SAA mechanism remains unclear.

Our approach involves noise tomography using short-period (1-10 s) Rayleigh waves enhanced by the multicomponent stacking technique. To measure the dispersion of the isolated fundamental mode Rayleigh waves accurately and effectively, we employ a modified machine learning algorithm based on the algorithm proposed by Yang et al.(2022) We employ the RecurrentResidual U-Net (R2U-Net) developed by Liao et al. (2021) for training. The model training data consists of dispersion diagrams from CCFs derived in various regions, including Taiwan, Japan, and the South Island of New Zealand. Approximately six thousand data are included in the training stage.

With the obtained dispersion data, we apply the wavelet-based multi-scale inversion technique to derive 3D models of Vs and Vs anisotropy. In this inversion process, the results from prior studies by Lee et al. (2023) serve as a priori constraint for the uppermost section of the model.

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Empirical Green's Function Retrieval of Infra-gravity Waves in the Pacific Ocean via Ambient Noise Interferometry

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Abstract

Infra-gravity waves (IGWs), characterized by gravity waves with longer periods ranging from 20 to 300 seconds, originate from the intricate interplay of nonlinear interactions involving wind dynamics, wave dispersion, coastal features, seabed topography, and various wave processes. In this study, we applied ambient noise interferometry to analyze cross-correlation functions (CCF) derived from a 10-year dataset collected by the Deep-ocean Assessment and Reporting of Tsunami (DART) system in the Pacific Ocean, yielding empirical Green's functions (EGFs) corresponding to IGW periods. The EGFs demonstrated notable propagating behavior, aligning with empirical wave dispersion relationships. Power Spectral Density (PSD) and spectrogram analysis unveiled seasonal patterns in North and Southeast Pacific Ocean stations, with winter intensity peaking in the former and summer in the latter, resembling IGWs observations from WAVEWATCH III. We combined the ray path from Fast Marching Surface Tomography (FMST) to thoroughly explore the seasonal variation of IGWs in intensity and propagation direction, aiming to establish potential links to climate models and to identify the sources of IGWs. Our results reveal that during periods of heightened winter Westerlies, storm activity predominantly fuels the source energy of IGWs. This inference is supported by the west-to-east propagation direction of IGWs along the Aleutian Islands, aligning with the movement of storms. Conversely, when Westerlies weaken, whether in winter or summer, shoreline reflection emerges as the primary source energy for IGWs. Additionally, we measured seismic velocity changes (dv/v) and inferred fluctuations in both internal and external factors that could influence the observed dv/v.

Keywords: Ambient noise interferometry, Empirical Green’s function, Infra-gravity waves, Seasonal variations, Tsunami.

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Recipe For Regular Machine Learning-based Earthquake Cataloging: A Systematic Examination in New Zealand, from Local to Regional Scale

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Abstract

Machine learning-based algorithms are emerging in mining earthquake occurrences from continuous recordings, replacing some routine processes by human experts, e.g., phase picking and phase association. In this study, we explore the combination of phase picker and phase associator with challenging application scenarios: the complex seismogenic structure, wide study area (15 degrees of both longitude and latitude and a depth of 600 km), hundreds of stations, and intensive seismicity during the 2016 M_w 7.8 Kaik ura earthquake that correlates with at least seven faults. The deep learning-based phase pickers usually follow the prototype of PhaseNet, which maps the phase arrivals into truncated Gaussian functions with a customized model. Recent studies have shown poor generalizability of the advanced models on data out of the training distribution. In this study, we argue that appropriate data augmentation enables the RED-PAN model, trained on the Taiwanese data, to generalize well on New Zealand data even under intense seismicity. We applied RED-PAN on year-long continuous recordings over 439 stations of the GeoNet during 2016 and 2017. RED-PAN produces approximately three million P-S pairs over the New Zealand-wide network, enabling the exploration of the advanced phase associators' robustness on local and regional scales and under intense seismicity, e.g., back-projection, GaMMA, and PyOcto. Finally, we developed a six-stage automatic pipeline producing a high-quality earthquake catalog: phase picking, phase association, 3-D absolute location by NonLinLoc, magnitude estimation, weighted template matching, and 3-D relative location by GrowClust.

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Advancing Earthquake Catalog Construction in Southern Taiwan Through Integrating Machine Learning with Existing and SALUTE Station Data

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Abstract

Accurate earthquake catalog construction is crucial for comprehending tectonic processes and mitigating associated hazards in regions with active faults and high seismicity, like Southern Taiwan. Traditional catalogs often suffer from incomplete detection and tedious manual efforts. To address this, we developed a regional earthquake catalog using machine learning (ML) by integrating data from seismic stations including CWASN, BATS, and the SALUTE project since 2021. SALUTE, deployed since October 2021, offers unprecedented spatial coverage, particularly along the active Chaochou Fault and across the difficultly accessible mountain range and eastern offshore area.

ML-based models like EQTransformer and PhaseNet, trained on labeled seismic signals, have shown effectiveness in detecting seismic events. In this study, we employed SeisBench, a Python package, to access the related ML algorithms and trained models for automatic earthquake location. We first adopted EQTransformer and PhaseNet models to pick P and S phases from three-component, pre-processed velocity waveforms. The Gaussian Mixture Model Associator (GaMMA), an unsupervised clustering algorithm, was then utilized to group a set of picks of both arrival times and amplitudes from all stations into clusters originating from the same causative event and determined the event's source parameters of origin time, hypocenter and magnitude through maximizing the log likelihood function given by

the sum of log-Gaussian mixture distribution of these picks. From one-day data of the CWASN stations only, our preliminary test located two times as many events as those reported in the CWA catalog. This approach demonstrates the potential of ML methods in refining earthquake catalogs in Southern Taiwan, which would significantly contribute to our comprehensive understanding of seismogenic structures and seismic risks in this region.

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Measuring near-surface S wave velocity in southern Taiwan from teleseismic receiver functions

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Abstract

Near-surface S-wave velocity (NSV) strongly impacts seismic wave amplification, crucial for predicting the intensity and characteristics of ground shaking during an earthquake, particularly in high seismic hazard regions like Taiwan. However, current seismic tomography models have limitations in accurately resolving shallow velocity structures. To address this, various methods have been attempted, including in-situ downhole logging, resonance peak analysis of microtremors, and lag time of body waves extracted from cross correlation functions of earthquake coda waves between co-site surface and borehole stations. In this study, we employed an alternative approach using teleseismic receiver functions (RFs) to determine NSV as described by *Svenningsen & Jacoben* (2007), which is not implemented in Taiwan before.

Recently, SALUTE (Southern Array for the Lithosphere and Uplift of Taiwan Experiment) initiative deployed a dense broadband seismic array across southern Taiwan, positioned at the transition zone from subduction to collision, and recorded high-quality teleseismic waveform for NSV measurements. We selected events with Mw $\geq$ 5.5 and epicentral distances of 28-95 and computed Z (vertical) and R (radial) RFs using an iterative time-domain deconvolution. Only RRFs with RMS misfits $\leq$ 0.3 and P pulse offset times within ±0.5 s were retained for further analysis. NSV is derived from the R-to-V RF amplitude ratio at zero time, solely based on the incidence angle of a P wave and its ray parameter. The NSV variation greatly agrees with near-surface geology, lower in the sediment-covered western coastal plain and higher in the crystalline massifs of the Central Range. In future investigation, we plan to construct apparent S-wave velocity, Vs,app(T) , as a function of the smoothing time window T applied to the RFs. It can be inverted for depth-varying S-wave velocities, enriching our understanding of the lithospheric structures and mechanical properties in southern Taiwan.

Key words: SALUTE, near-surface S-wave velocity, teleseismic receiver functions, southern Taiwan, apparent S-wave velocity

Tidal sensitivity and focal mechanisms of tectonic tremors in southern Central Range, Taiwan

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Abstract

In Taiwan, tectonic tremors are active in southern Central Range. They are found to be highly sensitive to small stress changes induced by hydrological and tidal forcings, which can be regarded as an indicator of stress at depth. Mounting evidences suggests that the tremors, presenting slip phenomena at the lower crust, play crucial role in the long-term assessment of largest earthquake potential. This study attempts to update the tremor catalog from 2012-2017 and establish their spatio-temporal patterns. With 2013 tremor events identified in southern Central Range (duration: 100 to 3053 sec), strong associations were found between tremor activities and tidal periods. Using the method proposed by Yabe et al. (2015), we found much higher tidal sensitivity (α ~0.7) in Taiwan comparing with subduction zones such as Nankai (α = 0.41) and Cascadia (α = 0.38). This implies that additional factors or specific environments may be needed, to explain this strong tidal modulation in Taiwan. Moreover, over 80% of tremors coincided with lower precipitation periods, with similar correlations seen in air pressure (63.71%) and groundwater level (63.59%). Given synchronized annual hydrological and meteorological cycles with tidal cycles, we hypothesize that hydrological loadings may amplify tremor occurrence annually. Furthermore, more tremor clusters have been found along the mountain belt (Ide and Chen, 2024), they exhibit similar annual elevation of the occurrence without clear link with shallow structures. In order to understand the hosting structures, we also determine the focal mechanisms using moment tensor inversion in a frequency band of 0.02-0.05 Hz. Resulting fault orientations are mainly perpendicular to the mountain belt in Taiwan, consistent with the ones inferred from background seismicity near the tremors clusters.

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Travel-time and waveform anomalies in Southern Taiwan Using SALUTE Array

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Abstract

The Southern Array for the Lithosphere and Uplift of Taiwan Experiment (SALUTE) represents an avant-garde initiative designed to intricately dissect the crust-mantle interface within the subduction-collision nexus of southern Taiwan and its eastern maritime boundaries. Initiated in October 2021, this program has meticulously orchestrated the deployment of 29 broadband seismic stations on land, complemented by 8 broadband ocean bottom seismometers (BBOBSs) in adjacent marine territories. This strategic arrangement aims to elucidate the lithospheric intricacies birthed from the Eurasian plate's convergence with the Luzon arc. By harnessing the analytical power of ambient noise alongside earthquake waveform data, SALUTE seeks to offer unparalleled insights into the orogenetic mechanisms and evolutionary trajectory of Taiwan's terrain. In this investigation, we elucidate the average travel-time anomalies beneath the observation stations, assimilating data from global events across diverse azimuthal orientations. Notably, the western foothills exhibit pronounced travel-time delays, indicative of distinctive subsurface processes. Conversely, the central range is characterized by negative travel-time anomalies, suggesting the presence of a subducting slab beneath southern Taiwan. Prospective analyses of waveform and amplitude anomalies stand to further delineate the intricate morphology of this subducting slab, offering a nuanced understanding of the region's geodynamic framework.

Keywords: Southern Taiwan, SALUTE, travel-time anomalies, waveforms

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Exploring Seismic Discontinuities of the Subducted Eurasian Continent beneath Southern Taiwan and Eastern Offshore Region with CCP Stacking of Receiver Functions

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Abstract

Southern Taiwan and its eastern offshore region lie in a pivotal intersection from continental subduction to arc collision, making it significant for studying subduction-collision structures and orogenic processes. In this study, we employ common-conversion point (CCP) stacking of receiver functions (RFs) to image discontinuous features of the subducted Eurasian continent and Luzon forearc beneath this critical transition zone. We have employed a free-surface transformation (Kennett, 1991) on 3-component waveforms, derived from teleseismic earthquakes 29-95 degrees away. Then, a frequency-domain deconvolution was applied, separating the longitudinal or P component from the SV component. Additionally, we apply a resonance removal filter (Yu et al., 2015) to mitigate sediment and water reverberations at land stations in western coastal plains and ocean-bottom seismometers on seafloor offshore SE Taiwan. After correcting Ps-P time difference (Xu et al., 2018) using a 3D tomography model (Huang et al., 2014), we migrate P RFs from time to depth axis every 1-km and stack amplitudes at common-conversion bins. The resulting CCP image reveals significant lateral variations of the upper/lower crust interface and the Moho of the Eurasian continent, which are 15 km and 25 km deep, respectively, beneath the western coastal plain. The relatively thin crust implies the Eurasian crust has been stretched and thinned by rifting extension. Moreover, the Moho is nearly vertically offset by ~10 km at about 10 km west of the CCF. Then progressively deepens toward the east and begins to descend steeply down to at least 80-100 km beneath eastern Taiwan and offshore region.

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2021 壽豐地震序列分析

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摘　要

台灣為歐亞板塊和菲律賓海板塊的交界處，每年平均會發生超過 20,000 次地震，因此在人口稠密的台灣，研究和觀測地震重要性可見一斑。位在東部的花東縱谷，地震活動非常活躍，歷史上也發生過許多起造成傷亡的地震事件。從 2021 年 4 月至 8 月止，花蓮縣壽豐鄉發生了一系列地震，其中在 4 月 18 日發生的主震規模為 6.2，對當地造成了一些災情。據中央氣象署地震測報中心統計，此地震序列期間共發生多達 11 次規模 5 以上的地震，且有逐漸往東、往北、由深入淺移動的趨勢。

為了研究此地震序列的孕震構造、地震機制及物理行為等，及評估流體是否介入，本研究使用機器學習演算法的流程及步驟，幫助我們減少地震波相誤檢、漏檢率，以獲得可信度、品質更高及數量更多的地震資料，進而提昇對該區域地震災害、影響的評估能力。本研究使用中央氣象署地震觀測網 (CWASN) 、台灣寬頻地震觀測網 (BATS) 和台灣強地動觀測網(TSMIP) 於 2021 年 4 月至 8 月的連續地震觀測資料作為原始資料，運用 RED-PAN 地震相位挑選方法進行潛在 P、S 波到時的挑選，並將挑選出的 P、S 波到時進行初步的 Back-projection (反投影地震定位) 。接著運用使用三維速度構造模型的 NonLinLoc (非線性定位方法) ，使得定位結果能更加精確。而後，經規模評估並生成初步地震目錄後，再運用波形相似度尋找更多遺漏小地震的 WTMA (Weighted Template-Matching Algorithm) 以利於提供更完整、豐富的地震目錄。

現階段運用 NonLinLoc (非線性定位方法) 所得出的研究成果中，可由時間分佈和剖面的觀點分別說明。4 月至 8 月的地震序列逐漸由西南 (縱谷的中央山脈一側) 往東北 (縱谷的海岸山脈一側，甚至出海) 移動，與中央氣象署的地震序列趨勢相符，定位出的地震數量也明顯多於中央氣象署的原始資料；而在花蓮縣壽豐鄉附近的剖面呈現兩條傾向相反的線形，與現階段學界研究成果相符。另外，在花蓮市近的剖面較無明顯線形趨勢，多呈現較高角度且混雜的地震群集，未來會致力於研究此區域附近地震序列是否與流體參與有關。

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利用機器學習對多測站波形進行地震規模評估

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摘　要

摘要地震規模是地震能量釋放的重要指標，也是地震預警系統 EEWs(Earthquake Early Warning system)是否發布警報的重要參考依據，因此如何快速且精確的評估地震規模是一個重要的問題。現在 EEWs 主要計算單測站 P 波到後前數秒的物理參數，例如：τ_c(特徵週期)和P_d (最大上下動)...等，進行統計回歸後來評估規模，然而只利用單測站評估規模會因為震源效應和場址效應產生較大的誤差，如果改為利用多測站同時評估規模，因獲取的資訊較多，期望可以提升精確性和提升評估速度。為了改善 EEWs，我們提出一個機器學習模型來評估規模，因需要能夠在多測站波形資料內提取物理特徵，我們選擇 FNO(Fourier Neural Operator)來建立機器學習模型。FNO 能將波形資料進行傅立葉轉換至頻率域中進行學習，且經過證明能有效的學習物理模型，並且能夠利用多站波形資料進行評估，所以我們利用 FNO 來提取波形特徵，最後將特徵進行回歸後評估。在訓練及資料增強方面，我們使用規模大於 3.5 的地震波形資料來進行訓練，並且使用時間窗格來模擬即時的地震波形輸入，將隨機排列輸入測站、加入噪訊作為資料增強的方式。我們期望此模型能夠優於現有的其他模型，提供更準確的快速地震規模評估。

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大屯火山地區地震序列及孕震構造分析

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摘　要

大屯火山群是台灣本島內唯一一座活火山，雖然帶來豐沛的地熱資源，但將來倘若噴發絕對會造成大台北地區將近 700 萬人口的生命受威脅，因此，唯有更瞭解火山，才能有效降低災害造成的影響。

本研究基於中央氣象署、大屯火山群地區監測網及 Formosa Array 挑選在 2019 年及 2020 年地震活動度較高期間，約莫 7 個月的地震資料，首先使用 RED-PAN (Real-time Earthquake Detection and Phase-picking with multi-task Attention Network) 是利用深度學習方法進行連續資料的地震偵測及波相判釋，接著使用反投影法（backprojection）及 NonLinLoc 將地震初步定位，再利用 Weighted Template Matching Algorithm （WTMA）的方法，以被 RED-PAN 判斷為地震之波形作為模板，利用此模板對連續地震波形進行波形相似度的搜尋，尋找肉眼無法辨別的地震事件，建立更小規模的地震目錄，希望對地下細部構造有更好的瞭解，最後利用 GrowClust3D 相對重新定位方法，使地震依照其波形相似度及走時差分群定位。此外，使用地震規模較大事件之 P 波上下動，逆推大屯火山區域地震之震源機制解，以及計算 b-value 探討地震序列是否是一般地震或群震。

本研究希望從地震數量、時空分布、震源機制解等，瞭解大屯火山地區之孕震構造。研究結果顯示，我們找到的地震數量大於氣象署，且得到更完整的地震目錄，這對於構造分析很有幫助，例如，在紗帽山、大油坑、七星山附近地下都有發現一些密集的地震分布。b-value 結果顯示，在大油坑及七星山周圍 b-value 呈現大於 1，指示著可能有流體引發的地震，而在紗帽山東側以及大油坑東北側 b-value 小於 1，指示著可能由構造活動引發地震為主。

本研究方法對於地體構造之分析或解釋有很大的幫助，此外，尋找群震位置、微震監測及地震危害度分析，對於地熱發展至關重要。

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大海撈針：臺灣東部大理岩體之棘皮動物化石保存潛力初探

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摘　要

臺灣石灰石礦主要來源為石灰岩和大理岩，而後者之蘊藏量佔比逾99%。前人研究同位素資料顯示，臺灣東部變質岩區大理岩之原岩沉積環境主要為海洋大陸棚之生物礁體。上述大理岩礦物成分以方解石為主，因受強烈變質作用，於露頭及薄片標本中可觀察到粒狀變晶、分凝條帶、柔性褶皺、縫合線構造和糜嶺狀構造。當原本富含化石之石灰岩受到如此高度變質作用時，會產生變形及重結晶，往往使化石形態難以辨識而無法鑑定。根據前人報導，大南澳片岩中保存有棘皮動物化石；本團隊將重新檢視現有標本材料，觀察其特有之井骨微結構。此外，將重新採集中橫公路東段沿線地層中大理岩樣本，透過製作岩石薄片方法探究其化石保存潛力，進一步尋找棘皮動物化石證據。

關鍵詞：太魯閣、大理岩、九曲層、砂卡礑溪、棘皮動物門

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全新世早期遺址貽貝殼體穩定同位素紀錄所反映之馬祖亮島地區古環境

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摘　要

本研究分析了馬祖亮島11件島尾遺址Ⅰ（距今約8300~7400年前）與12件島尾遺址Ⅱ（距今約7600~7400年前）的遺址貽貝殼體；此外，分析所採集馬祖南竿地區的18個現生貽貝樣本，和97個馬祖南竿與北竿地區海水樣品的穩定同位素成分，以重建馬祖地區全新世早期的古環境。

南竿地區水樣品的平均氫、氧同位素數值分別為-2.9 ± 2.6‰和-0.8 ± 0.4‰（平均值 ± 1σ；N=49；V-SMOW）；北竿地區水樣品的平均氫、氧同位素數值分別為-2.7 ± 2.5‰和-0.8 ± 0.4‰（N=48）。根據觀察到的同位素數值和鹽度紀錄，南竿、北竿水體的氧同位素值呈現季節性波動，並與淡水與海水混合的量有關。

馬祖亮島島尾遺址Ⅰ貽貝殼體的平均碳、氧同位素數值，分別為0.5 ± 0.5‰和-1.2 ± 0.6‰（N=531）；島尾遺址Ⅱ遺址貽貝殼體的平均碳、氧同位素數值分別為0.7 ± 0.4‰和-1.6 ± 0.6‰（N=394）。馬祖亮島遺址Ⅰ與 Ⅱ之遺址貽貝殼體的平均氧、碳同位素數值分別有0.2‰及0.4‰的差異，反映亮島於約8300~7400年前之間與約7600~7400年前之間的古環境可能有些許差異。

遺址貽貝殼體的平均碳同位素數值，比現生未煮沸貽貝殼體的平均碳同位素數值大約1‰，可能反映出8300~7400年前馬祖地區水體的基礎生產力較高。遺址貽貝殼體的平均氧同位素數值，比現生貽貝殼體的平均氧同位素數值大約0.6‰，顯示當時的海水溫度可能比現在低約2~3℃及/或當時的淡水注入量較少。現生和遺址標本中都觀察到氧同位素數值的季節性波動，根據最完整的13個遺址貽貝標品，採收季節分別為春夏（N = 5）、夏秋（N = 4）和冬季（N=4），採收季節分布大致平均。

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俄羅斯南烏拉山脈洞穴石筍之定年紀錄

Age Dating of Stalagmites from South Ural Mountain Caves, Russia

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摘　要

石筍為一種洞穴碳酸鹽沉積，是研究古氣候的絕佳材料。本研究使用 ^{14}C 定年法，並搭配 ^{210}Pb 和 $^{230}Th/U$ 定年法為 Ikenskaya 洞 (54º43’1’’ N, 57º18’25’’ E)的石筍 IKEN-1 及 Oktyabrskaya 洞 (54°10'09.7"N, 56°50'56.5"E)的石筍 OTAR-1，建立年代模型。用 alpha 能譜儀 ^{210}Po 獲得石筍的 ^{210}Pb 定年結果顯示，IKEN-1 頂部老於 200 年而 OTAR-1 頂部小於 120 年。$^{230}Th/U$ 定年結果指示，IKEN-1 在近千年到 4240±80 年間生長（最頂部的 $^{230}Th/U$ 因含大量 ^{232}Th而偏老）。OTAR-1 從 4962±738 年前生長至今。由於石筍的鈾含量不高（低於 0.5ppm）而釷含量較高，使得鈾系定年的誤差很大。因此，高密度的 ^{14}C 定年可以推估死碳效應(dead carbon influence, DCI)，得到相對精確的年代模型。目前，從 IKEN-1 的 18 個 ^{14}C 年齡結果，發現該石筍受死碳影響很小，頂部校正 ^{14}C 年齡為 615±35 cal yr BP, 印證 ^{210}Pb 定年結果。底部 ^{14}C 年齡為 3515±150 cal yr BP，小於 $^{230}Th/U$ 年齡。OTAR-1 的 19 個 ^{14}C 年齡結果表明，該石筍受死碳影響使 ^{14}C 年齡偏老 920 年，扣除這個死碳年齡，該石筍的 ^{14}C 年齡基本與 $^{230}Th/U$ 年齡一致。根據詳細的 ^{14}C 定年結果，用 Bacon 模式建立了兩個石筍的

年齡模式。高分辨率的碳氧同位素記錄（IKEN-1 有 1155 個樣品，OTAR-1 有 2010 個樣品）將為我們提供研究地區過去 5 千年的氣候和環境變化記錄。

關鍵字：石筍、^{14}C 定年、^{210}Pb 定年、$^{230}Th/U$ 定年、石筍碳氧同位素

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臺灣南部恆春西台地貓鼻頭石灰岩層序地層與沉積環境

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摘 要

恆春半島蘊涵臺灣造山作用最年輕一期的層序，增積岩體在劇烈抬升的過程中，發育相當規模的碳酸鹽岩覆蓋在海相沉積岩之上。其中恆春斷層以西的恆春西台地，為一第四紀隆起且西高東低的台地，於現今海平面之上主要由更新世的地層所組成。在恆春西台地南端海岸出露的貓鼻頭石灰岩相較其他地點的恆春石灰岩具有獨特岩相組成，其普遍存在的大型交錯層在過去的沉積環境解釋中就有不同見解。經由野外調查，近乎水平層理的貓鼻頭石灰岩自海水面以上出露厚度可達 37 m，且岩層中主要發現的沉積構造多為圓丘狀交錯層理（hummocky or swaley cross-stratification，簡稱 HCS/SCS）。

貓鼻頭石灰岩主要可分為三種岩相：（一）生物碎屑泥粒灰岩（Bioclastic Packstone Lithofacies）、（二）生物碎屑泥粒-顆粒灰岩（Bioclastic Packstone-Grainstone Lithofacies）和（三）生物碎屑顆粒灰岩（Bioclastic Grainstone Lithofacies）。岩層中的碳酸鹽顆粒主要由生物碎屑組成，一般小於2mm，多屬於顆粒支持的碎屑性石灰岩。顆粒間在交錯層內有明顯排列，大型生物殼體如藤壺、海膽、貝類等磨損程度高，顯示在強烈水流下被搬運和迅速堆積。而從其較小型化石的埋藏狀況中，發現浮游性有孔蟲，和大型有孔蟲、小型底棲性有孔蟲、苔蘚蟲等混合的生物殼體，可能指示沉積物曾經過水流翻動，擾亂海床沉積物使兩者混合。此外，於交錯層底部也曾發現生物擾動現象。依照超微化石與浮游性有孔蟲分析結果，貓鼻頭石灰岩的生物地層帶相當於 NN19 和 N22 化石帶，其沉積年代可能介於 1.7Ma 與 0.61Ma 之間。總結岩相組合和特性，本研究認為貓鼻頭石灰岩是暴風環境為主的產物，經高能量的波浪作用搬運、並經由快速沉積所形成的再積石灰岩（redeposited limestone）。

關鍵字：恆春西台地、恆春石灰岩、貓鼻頭石灰岩、沉積環境、圓丘狀交錯層理

臺灣南部四溝層鹿屬下頜骨化石之初步研究

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摘　要

臺灣南部的恆春西臺地地區，出露了富含化石的四溝層，擁有豐富的無脊椎化石，哺乳類化石相較起來略較為稀少，過去在此地層發現的哺乳類有象、犀、鹿，以及鯨豚等物種。除了國立自然科學博物館於 2022 年在此地層發現了保存極為完整的鯨魚化石，絕大多數的標本都殘缺不全。本研究報導一件發現自頂頭溝地區的完整鹿科下頜化石。藉由針對下頜頰齒的線性測量以及與臺灣現生鹿科動物的比較，確認該標本的種屬分類。結果顯示，根據牙齒尺寸，可以得知此鹿科動物應為鹿屬的物種。目前臺灣周邊地區鹿屬化石有早更新世到中更新世的似步氏鹿(*Muntiacus* cf. *bohlini*, Otsuka 1984)、鹿未定種(*Muntiacus* sp., Otsuka 1984)以及在澎湖地區所發現的晚更新世臺灣山羌(*Muntiacus reevesi Micrurus*, 陶錫珍 1991)。在頂頭溝地區的四溝層所發現的鹿屬化石，顯示在更新世時期臺灣有多種鹿科動物，且四溝層的鹿科化石研究將有助於了解臺灣更新世晚期鹿科動物組成及分布，進一步推論恆春西臺地地區於晚更新世的生態環境。

關鍵字:鹿科動物、小型鹿、牙齒形態學、晚更新世、恆春

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建立臺灣海域孕震構造資料庫

Constructing the Offshore Seismogenic Structure Database

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摘　要

臺灣地區有許多地震活動與孕震構造，若能事先掌握構造的位置、發震規模與活動性，便能用於地震危害度模型計算以降低災害損失。由於海域地質調查不易，決定海域構造的位置與活動性是地質研究的重大挑戰，使得過去臺灣孕震構造研究僅聚焦在陸地區域。本研究整合已發表的震測剖面與海底地形資料，透過分析不連續反射訊號是否切穿海床以及海床線型的側向延續性，目前建立了54條臺灣周邊海域可能發生規模6.5以上地震的孕震構造位置與其地下幾何。

根據構造運動型態與現有調查的差異，本研究提出三種估計海域構造長期滑移速率的方法，並利用地震規模搭配長期滑移速率獲得地震再現週期。研究發現，構造活動速率較高的區域位於琉球隱沒系統上盤與東部外海，在考慮無震潛移作用後的長期應力累積速率仍可能超過15mm/yr，地震再現週期小於1000年。而其餘區域的海域構造雖然仍具有發生大地震的能力，但活動速率較低，多小於5 mm/yr，因此地震再現週期大部分長於6000年。此計算成果符合臺灣各區域的地質背景，例如相對穩定的臺灣海峽與北部外海的構造活動性較低，而東部外海構造活動速率較高且由南往北增加，此趨勢可能反映臺灣島的碰撞造山過程。若將外海構造與臺灣島上構造的水平縮短速率加總，其結果與區域板塊縮短速率相近，代表本研究所計算之海域構造活動速率範圍應頗為可靠。

未來希望此資料庫能促進更精準的地震危害度計算，進一步提高臺灣防震防災的能力。對於海洋資源的開發與近海的各項建設，此資料庫也可提供重要的基礎地質資訊。在臺灣的地震科學研究中，此成果也有望促進孕震構造研究朝向海洋發展。

關鍵詞：孕震構造、地震災害、地震規模、長期滑移速率、地震再現週期
Keywords: Seismogenic structure, Seismic hazard, Earthquake magnitude, Long-term slip rate, Earthquake recurrence interval

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Lateral subduction zone termination against a transform fault in the Southeastern Solomon Islands

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Abstract

Lateral termination of subduction zones take place against a transform fault whose near-vertical, lithosphere-scale tip propagates in a direction opposite to that of subduction. In this study, we investigate the geometry of the termination of the South Solomon subduction zone against the Makira-Santa Cruz transform where southwestward propagating mode-III vertical tearing has been proposed to occur. The South Solomon subduction zone is highly seismically active, and there were two moderate earthquakes (Mw 6.3 and 6.0) that occurred on January 27th and 29th, 2020. The entire foreshock-aftershock sequence was recorded on a new regional seismic network that has been operational since October 2018. The majority of hypocenters form a single cluster, deepening northward from near the surface to >100 km depth beneath Makira Island. In the southeast, hypocenters can be broadly divided into two clusters; a shallow cluster at roughly 0 to 25 km depth, and a second cluster between about 50 km and 100 km depth. We use this earthquake sequence to calculate a new 1D velocity model and relocate the foreshock and aftershock events. Based on the spacial distribution of the foreshock-aftershock sequence, together with focal mechanism data from the Global CMT database, we confirm that the South Solomon subducting slab terminates abruptly against the Makira-Santa Cruz transform along a near-vertical mode-III tear. Furthermore, a seismic gap at a depth of 25 to 50 km within the southeastern part of the South Solomon slab may image horizontal tearing along the western margin of the plateau. In addition to the earthquake distribution of the seismic cluster beneath Makira Island, we also observe a contrast in seismograms between shallow (<50 km) and intermediate-depth (>50 km) earthquakes. The deeper events

show stronger high-frequency signals and large-amplitude onset for P waves, which might be related to the slab-guided waves propagated through the Australian plate.

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The characteristics of the Chihshang segment of the Longitudinal Valley Fault System, eastern Taiwan, assessed by historical aerial photo reconstructions

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Abstract

The Longitudinal Valley Fault (LVF) System is one of the most active fault systems in Taiwan. Between Yuli and Luyeh, the Chihshang segment of this fault has been proposed as an active creeping fault with a high slip rate that was estimated at approximately 2-3 cm per year. However, historical earthquake records indicate that surface ruptures of the November 1951 earthquake were observed only from Yuli to Chihshang, not between Chihshang and Luyeh in the Guanshan area. In fact, only limited studies were focused on the fault segment in the Guanshan area, partly due to the fact that human activities have significantly modified the fault trace and geomorphic features in this area.

Advancements in photogrammetry techniques have recently facilitated the utilization of historical aerial photos to reconstruct old landforms that may have been obliterated by human activities. Therefore, we used historical aerial photos taken in 1968 and 1969 to obtain a historical Digital Surface Model (DSM) and orthoimages using Structure from Motion (SfM) and Multi-View Stereo (MVS) methods. With the historical DSM and orthoimages, we mapped structural scarps along the fault segment in the Guanshan area. We also measured current scarp heights using Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) in the field.

Our results show that, by comparing the river terrace riser heights in the reconstructed DSM and present-day measurements, the error of the reconstructed DSM is generally much lower than 1 m. Therefore, structural scarps that are much higher than 1 m can be reliably identified with reconstructed DSM using historical aerial photos. Furthermore, the results show that the characteristics of structural scarps appear to change in different parts of the study area. This indicates that the reconstruction of historical aerial photos can be used to retrieve previous landforms that were significantly modified by human activities and to identify active faults within those areas.

Keywords: Aerial photos, Longitudinal Valley Fault, Digital Surface Model (DSM), Structure from Motion (SfM), Multi-View Stereo (MVS)

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沉積物均衡調整作用對臺灣地區海水面變化與其紀錄之影響

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摘　要

古海水面的變化歷史對於瞭解沿海的構造活動而言至關重要，近年來學界逐漸發現，地區性的海水面會受到侵蝕與沉積產生的沉積物均衡調整作用（sediment isostatic adjustment，SIA）影響，在不同區域有不同的變化模式。如一地若發生侵蝕會減輕岩石圈荷重，而產生均衡抬升，造成海退；相反地，沉積會增加荷重而使岩石圈均衡下沉，造成海進。而臺灣作為全球侵蝕與沉積速率最快的地區之一，過去有關海岸抬升的研究卻都沒有考慮此效應，將造成沿海構造抬升速率的估算失準。本研究即透過建立臺灣與周圍海域的沉積物傳輸歷史，並以此作為輸入進行海水面模擬，來定性且定量地瞭解在最近一次冰期與間冰期循環中，SIA對於臺灣各海岸線海水面變化的影響。為建構完整的沉積物傳輸模型，本研究整合全臺所有已發表的流域平均侵蝕速率與磷灰石核飛跡年代，來建立山區的侵蝕速率分佈圖；並整合平原區與海域岩心中的各種定年資料，以及由震測剖面所得之沉積物等厚度圖，來製作平原區與周圍海域的沉積速率分佈圖。另外，也考量各處低海水面與高海水面時期的沉積速率不同，而設計隨時間變化的沉積物傳輸模型。海水面模擬結果顯示，臺灣沿海的海水面變化與古海水面紀錄，確實很大程度地受到SIA作用的影響。在西北部苗栗沿海、花東海岸受到附近山脈快速侵蝕造成的均衡抬升影響而海退；西南海岸、恆春沿海、蘭嶼則是受附近平原區與海域快速沉積的影響而均衡沉降，造成海進。這可能是世界上第一次觀察到海岸線在如此短距離內（約100公里）就呈現不同的均衡模式，而這正是因為臺灣區域有著極高的侵蝕與沉積速率，且臺灣彈性岩石圈的厚度較薄所致。此外，SIA於沿海造成的相對海水面變化，在千年尺度可達數十公尺，在十萬年尺度則可超過200公尺，也是至目前所觀察到之SIA造成的海水面變化中最大的。最後，本研究透過模擬出之各海岸的相對海水面曲線，得以重新檢視各沿海的構造抬升速率，發現以往在未考慮SIA作用時所計算出的構造抬升速率可能分別低估及高估多達90%和60%以上，將顯著影響我們對於海岸附近之活動構造的瞭解，也因此需要大幅度修正。這些結果都顯示臺灣未來在使用古海水面指標來瞭解沿海的構造活動時，定量化地考慮SIA的效應是相當重要的。

關鍵詞：均衡調整作用、侵蝕與沉積作用、海岸抬升速率、構造地形學、新期構造運動。

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Geological Mapping and structural surveys of newly exposed formations due to glaciers retreat in northern Kaffiøyra, western Svalbard.

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Abstract

The Svalbard archipelago is located between eastern Greenland and the northwestern Barents Sea Shelf between 74° to 81°N and 10° to 35°E. This archipelago is on the margin of the Eurasian Plate and the North American Plate and belongs to the High-Arctic region. The geological time scale of Svalbard ranges from Neoproterozoic to Neogene and present times. Due to glacier retreat, vast areas are being exposed to unexplored geological formations that can be detailed measured and surveyed.

In this study, we focus on the area in the south of glacier Aavatsmark in northern Kaffiøyra plain, western Svalbard. This area is characterized by a complex of fault zones belonging to the eastern boundary of the Hornsund Fault Complex (HFC), formed during the Eurekan deformation event. Our field investigation was conducted during the expedition in August 2022. We have found that this zone is characterized by both-dextral and sinistral Riedel shear components. This supports transpressional and transtensional deformation between Svalbard and Greenland during Eurekan orogeny, as reported in previous studies. Our fault zone analysis was measured in situ using the clinometer and supported by the UAS (Unmanned Arial System) missions, which aided in constructing detailed geological maps of this area through orthophotos and digital elevation models (DEMs). The boundary between Neoproterozoic and Ordovician/Silurian strata was identified based on metasedimentary successions.

The main objective of this research is to build a tectonic and geological model of the deformation zone along the boundary and understand the evolution of the deformation during the development of Eurekan Orogeny.

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Cenozoic Rift-Drift Transitions in the Hsuehshan Trough, Taiwan: Insights from Detrital Zircon Analysis

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Abstract

Understanding the sedimentary provenance of infill records within evolving sedimentary basins is pivotal for unraveling geological processes. In a rifting setting, syn-rift period is characterized by locally derived sedimentation due to active normal faulting. However, during the post-rift stage, thermal subsidence facilitates sediment influx from distant sources, resulting in a polymodal detrital zircon age spectrum indicative of diverse provenance. Unfortunately, previous studies in Taiwan have overlooked basin evolution, focusing solely on drainage system variations. To investigate the source-to-sink history of the Hsuehshan Trough from the Late Oligocene to Early Miocene, we compiled data from previous studies and conducted detrital zircon U-Pb dating on samples from the Wuchihshan to Shihti Formations in the well-studied Waimushan Profile by LA-ICP-MS. Our analysis reveals shifts in sedimentary provenance, aided by comparison with the well-explored Songliao Basin, employing a bivariate discrimination model.

This study incorporates eleven samples and 1,314 effective U-Pb detrital zircon dating data points. The lower Wuchihshan Formation exhibits a relatively simple age spectrum, reflecting a syn-rift signal, while the upper Wuchihshan and Mushan Formations depict a transitional stage. Notably, the Mushan Formation contains latest Paleogene detrital zircons which may correlate with igneous activity in northern Hsuehshan Trough and displays a distinct Cenozoic peak. The subsequent Taliao and Shihti Formations demonstrate a polymodal age distribution, indicating diverse provenance. Additionally, the presence of Eocene zircons in the Mushan Formation suggests the influence of breakup processes on sediment sourcing. All in all, these findings underscore the dominance of basin development processes in shaping sedimentary provenance. While the final results align with previous studies, we suggest an older boundary between syn-rift and transitional stages.

Keywords: Basin evolution, Hsuehshan Trough, and zircon U-Pb geochronology

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玉里斷層百年至千年尺度的活動特性與相關地形構造

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摘 要

玉里斷層位於縱谷中段，在1951年11月的池上—玉里地震序列後被提出，且在2022年關山—池上地震序列中亦於其斷層沿線與其南北延伸方向上觀察到一系列具有左移與逆衝分量的同震地表破裂。然而由於花東縱谷內的河流侵蝕與堆積作用強烈，且該斷層於近地表處的活動垂直分量較低，而使玉里斷層長期活動的證據不易保留，進而導致其具體位置與相關構造活動特性有所爭議。因此，本研究嘗試以2022年同震地表破裂資料作為基礎，藉由地形分析、野外測量與歷史圖資判釋等方法，結合野外地質調查成果，尋找玉里斷層沿線與其南北延伸上是否有百年至千年尺度的活動地形構造，進而了解該斷層於此尺度下的近地表活動特徵。

本研究透過由北往南五處地點的地形調查成果發現，玉里斷層沿線上多處低位沖積扇面可見地形變位之特徵。其中位於2022年地表破裂北界的苓仔溪沖積扇可見高約1.9公尺的地形撓曲，顯示與玉里斷層相關的活動構造可能往北延伸至此區。其斷層中段於玉里鎮區中除先前已被報導的湧泉與同震地表破裂等斷層特徵外，亦發現可能於1951年地震前即已存在，高約1.7公尺之撓曲崖，以及相關的撓曲地形面特徵。位於2022年地表破裂南段的崙天溪沖積扇前緣，於同震地表破裂西側亦可見沖積扇面撓曲，且於前述同震破裂位置向南延伸至石牌社區附近，觀察到與該構造相關的反斜崖存在。依據上述結果，本研究發現玉里斷層在縱谷中段確實存有不少相關活動地形證據，且於近斷層處造成約1到3公尺高，西高東低的地表變形。這些地形特徵在1951年前即可能已經形成，顯示該斷層在百年至千年尺度下是相當活躍的構造。

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Improving the structural geometry of a boundary fault with 3D LiDAR Geologic mapping: a case study of the Chuchih Fault in the Taoyuan quadrangle

應用光達三維地質製圖方法精進界限斷層之構造幾何：以桃園圖幅內的屈尺斷層為例

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Abstract

The geological provinces of Taiwan are classically divided into five units, including the Coastal Range, Backbone Range, Hsuehshan Range (HR), Western Foothills (WF), and the Coastal Plain. Most boundaries between these tectonic units are defined by major faults, though some of these boundary faults haven't been well defined and understood. Among them, the Chuchih Fault is traditionally defined as the boundary between WF and HR. However, evidence such as biochronological and structural research has made the distribution of the contact controversial. Biochronological research indicates that the Chuchih Fault is not the division between the Paleogene and Neogene strata, while some structural investigations suggest that certain segments of the Chuchih Faults lack the structural meaning of a "boundary fault". Due to limited exposure, there is insufficient field data near the Chuchih Fault within the Taoyuan geologic quadrangle area, and the detailed structural geometry remains unclear. In this study, Digital Elevation Modeling (DEM) derived from Light Detection and Ranging (LiDAR) is used to interpret macroscopic geological structures, which are often covered by vegetation. We used the open-access 3D DEM (20-meter resolution) and overlay it with a 2D high-resolution hillshade image, and explored the geology with multiple perspectives in a 3D GIS environment. A detailed geological map is produced near the Chuchih Fault within the Taoyuan quadrangle, presenting the geometry of faults and folds with wavelengths of several kilometers. The fault trace and displacement along the Chuchih Fault are modified, and several minor faults that may be related to folding are delineated. Additionally, there

are close to open synclines that plunge to the SW, with anticlines or faults in between. The method of applying LiDAR DEM to improve geologic structural mapping between WF and HR is feasible. The improved understanding of structural geometry in the study area suggests that the boundary between WF and HR should not be simply defined as a single fault, namely the Chuchih Fault.

Keywords：
3D Geologic mapping, LiDAR-derived DEM, boundary fault, Chuchih fault, Taoyuan quadrangle
三維地質製圖、光達產製DEM、界限斷層、屈尺斷層、桃園圖幅

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Foliation Pattern in the Southern Slate Belt of Taiwan: New Insights from 3D Mapping Using LiDAR DEM

利用光達地形三維製圖解析中央山脈板岩帶葉理分佈：以南部橫貫公路中段為例

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Abstract

Foliation mapping in strongly-deformed and exposure-limited terrain, such as the Central Range Slate Belt in Taiwan, has long been a challenge to be accurate. Despite LiDAR (Light Detection and Ranging)-derived DEM (Digital Elevation Model) providing effective results for 3D geologic mapping in the slightly-deformed-and-metamorphosed Hsuehshan Range, its application in the strongly-deformed, low-grade metamorphosed Slate Belt remains unexplored and uncertain. For better understanding the exhumation processes and constructing the foliation pattern in the Slate Belt of the southern Central Range, we draped a high-resolution LiDAR-derived DEM shaded-relief image over the 20-meter resolution DEM in stereo views and delineated structures-controlled planar features from different perspectives. Field mapping checks, structural analysis, and drone surveys were conducted along the Southern Cross-Island Highway. On the LiDAR DEM, abundant suites of planar features were identified, with two pervasive and penetrative suites standing out: a bedding (S0) and a tectonic foliation (Sf). Based on the geometry of the planar features and field observations, S0 is attributed to thick-layered metasandstone and metatuffaceous rocks, whereas Sf displays well-developed slaty cleavage and transposed layering. Our findings show that the regional pattern of S0 reveals a kilometer-scale, overturned, and tightly-folded synclinorium with an east-dipping axial surface. The increasing complexity of geomorphic features and characteristics toward the east of the mountain range corresponds with the progressively intense deformation observed in the field. This study supports the usefulness and precision of foliation mapping using LiDAR-derived DEM in strongly and pervasively deformed terrains. We demonstrate the existence of a synclinorium in the study area, as well as the progressive deformation of the Slate Belt from the west to the east of the Taiwan Central Range.

Keywords: LiDAR DEM, 3D Foliation Mapping, Slate Belt, Foliation, Synclinorium, Progressive Deformation

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以熱-力學耦合數值模擬探討臺灣弧前基盤缺失成因

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摘　要

台灣地處歐亞大陸板塊邊緣並與菲律賓海板塊交界，菲律賓海板塊以每年 70 到 80 毫米的速度向西北方向移動並與歐亞大陸板塊聚合，形成呂宋島弧與台灣造山帶。但在台灣造山帶中段呂宋島弧與歐亞大陸邊緣直接相連，缺失弧前基盤，此弧前基盤缺失現象亦廣泛出現於類似板塊聚合區域。過去研究認為此弧前基盤已隱沒至於菲律賓海板塊與歐亞大陸板塊之間。為了探討弧前基盤隱沒的機制，我們利用熱-力學耦合數值模擬，並結合地質資料，模擬岩石圈尺度的板塊隱沒到碰撞過程來探討台灣造山帶中段弧前基盤隱沒的動力學機制。
模擬結果表明，當隱沒板塊由海洋地殼過渡到大陸地殼時，因大陸地殼材質密度較輕，不易隱沒而造山形成的巨大塊體阻擋菲律賓海板塊向西北前進，讓弧前地殼撓曲下凹形成一個弧前盆地，盆地內開始堆積大量的沉積物。直到盆地中心破裂形成縱谷斷層，盆地東側島弧區域逆衝至盆地西側弧前基盤之上方，推擠盆地內沉積物快速抬升，最終弧前基盤隱沒至菲律賓海板塊之下。此模型解釋了弧前基盤缺失的原因、縱谷斷層形成的時間點，以及海岸山脈沉積物記錄到的劇烈上下運動，同時也解釋地表熱流的空間變化趨勢。

關鍵詞：弧陸碰撞、弧前基盤缺失、動力模型

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Thermo-mechanical models on the missing forearc basement in Taiwan

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Abstract

Taiwan is located at the edge of the Eurasian plate and borders the Philippine Sea plate. The Philippine Sea plate is moving northwestward at a speed of 70 to 80 mm/yr and is converging with the Eurasian plate, forming the Luzon arc and the Taiwan orogenic belt. However, in the middle section of the Taiwan orogenic belt, the Luzon arc is directly adjacent to the edge of the Eurasian continental margin, and the forearc basement is missing. This phenomenon of missing forearc basement is also widely observed in similar plate convergence zones. Previous studies have suggested that this forearc basement has subducted between the Philippine Sea plate and the Eurasian plate. In order to explore the mechanism of forearc basement subduction, we used thermal-mechanical coupled numerical simulations combined with geological data to simulate the dynamic mechanism of forearc basement subduction in the middle section of the Taiwan orogenic belt.

The simulation results show that when the subducting plate transitions from oceanic crust to continental crust, the continental crust has a lower density and is not easily subducted. The huge mass formed by the orogeny blocks the Philippine Sea plate from moving northwestward, causing the forearc crust to bend concavely and form a forearc basin. The basin begins to accumulate a large amount of sedimentary material. Later, the center of the basin breaks to form the Longitudinal Valley fault, the island arc to the east of the basin thrusts over the forearc basement, pushing the basin sediment to uplift rapidly, and finally the forearc basement subducts below the Philippine Sea plate.

This model explains the mechanism for the missing forearc basement, the timing of the formation of the Longitudinal Valley fault, and the dramatic up and down movements recorded in the sedimentary rocks of the Coastal Mountains. It also explains the spatial pattern of the surface heatflow.

Keywords : arc-continent collision, missing forearc basement, dynamic model

印尼蘇拉瓦阿甘火山快速稀土元素富集現象探討

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摘　要

蘇拉瓦阿甘（Seulawah Agam）是一座位在蘇門答臘島西北端的現生第四紀島弧火山，從該火山採集到的十一件火山岩滾石及露頭樣品中，有四件顯示異常高的稀土元素含量，且具少見的重稀土元素富集（La_N: 114-761; Dy_N: 29-141; Yb_N: 32-126）和強烈的負鈰異常（$(Ce/Ce^*)_N$: 0.28 - 0.67）；然而，除稀土元素以外，這四件特殊樣品的主、微量元素濃度及鍶、鈥同位素比值和其他樣品卻相當類似。本研究奠基於蘇拉瓦阿甘樣品的地球化學和岩石學資料，整合前人零星的文獻報導，為稀土富集與潛在的成礦作用提供制約。

岩象方面，所有樣品都具有斑狀組織和相似的礦物組成，唯一的差異在於特殊樣品中含有罕見的水磷鈰礦（rhabdophane，$(LREE)PO_4 \cdot H_2O$），偶見水磷釔礦（churchite，$(HREE)PO_4 \cdot 2H_2O$）。水磷鈰礦通常以斑塊的形式出現在基質中，或以晶簇狀出現在篩狀斜長石的縫隙中，亦或是置換磷灰石；水磷釔礦則可見於篩狀斜長石的縫隙中。以前人發表的稀土元素組成估算，普通岩樣只要含有微量的水磷鈰礦（< 0.11 wt.%）及水磷釔礦（< 0.09 wt.%）即可將稀土元素濃度提升至和特殊樣品相當；這與電子顯微鏡影像上的礦物面積估算相符，指示水磷鈰礦與水磷釔礦的形成是使特殊樣品稀土富集的原因。水磷鈰礦及水磷釔礦分別在攝氏 500 度和 200 度以上會轉變成獨居石及磷釔礦，為次生礦物；另外，強烈的負鈰異常需要鈰被氧化成不溶於水的四價離子而與其他稀土元素發生分異，因此本研究中的稀土富集現象為「近地表氧化環境中次生作用」的結果。

在近地表環境中，稀土元素能夠被酸性溶液溶解、隨之遷移，而前人研究對稀土元素的析出提出的機制包括溶液(1)與長石進行離子交換使 pH 值提升，導致稀土溶解度降低，或(2)於攝氏 250 度、100 巴的環境中與磷灰石交互作用。本研究中，含水稀土磷酸鹽礦物常伴隨篩狀斜長石出現或置換磷灰石，此結果分別支持了前述的兩種機制。值得注意的是，過去的研究曾根據岩石年代指出此富集現象需要 > 2 Myr 的發展，然而考量蘇拉瓦阿甘火山的形成時間，此種稀土富集其實可在< 0.3 Myr 內快速形成。

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臺灣東北角海岸萊萊地區中新世火成岩脈成因

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摘 要

一組在文獻中被紀錄為”煌斑岩”的中新世火成岩脈坐落於臺灣東北角海岸萊萊地質區。然而本研究發現岩樣中的角閃石屬於副礦物相，而黑雲母是角閃石蝕變產物，且樣本的MgO和K_2O豐度分別<8%和1.8%，以上特徵都與典型”煌斑岩”不符。樣本K_2O、Rb濃度與L.O.I.(5-11%)呈負相關，顯示蝕變作用。總體而言，MgO含量隨著SiO_2的降低以及TiO_2和Al_2O_3的增加而降低，儘管其意義尚不清楚。

其中一組樣品含有相對較高的 MgO（> 7%），其他主要元素的含量變化相當有限，它們被歸納為A組樣品。B組樣品是在給定的MgO含量下具有相對較高Na_2O含量的樣品。C組樣本的Na_2O、K_2O和MnO分佈範圍廣泛，MgO含量延伸至4.5%的低值。A組和B組樣本有明顯LREE-HREE 正相關性，而C組樣本的趨勢偏離到較低的HREE 值，這意味著成因差異。

在$^{87}Rb/^{86}Sr$-$^{87}Sr/^{86}Sr$ 圖中，A組樣品低於B組和C組的逆向趨勢線，顯示這些樣本至少涉及兩種端成分；低和高$^{87}Sr/^{86}Sr$端元分別被推論為地函和地殼成分。然而，地殼成分不可能來自岩脈的圍岩，因為它們的$^{87}Rb/^{86}Sr$ 值很高，推翻淺層地殼污染可能性。這項推論得到了$^{206}Pb/^{204}Pb$-$^{208}Pb/^{204}Pb$圖的支持，其中圍岩的$^{208}Pb/^{204}Pb$比率高於地殼成分所需的比率。據此，認為來源污染是造成來岩脈Sr和Pb同位素特徵的原因，然而汙染物的性質需要進一步明確。

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Petrogenesis of the Miocene igneous dikes in Lailai, northeastern coast of Taiwan

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Abstract

A set of Miocene igneous dikes occurs in LaiLai area at the northeastern coast of Taiwan. They were referred to as “lamprophyric rock” in some documents. However, our samples show that amphibole is an accessory mineral and biotite occurs as an alteration product from amphibole. Moreover, they have MgO and K_2O abundances < 8% and 1.8%, respectively. All these features are inconsistent with being “lamprophyric rock”. Their K_2O and Rb abundances are inversely correlated with L.O.I. content (5–11%), reflecting alteration. As a whole, the MgO content decreases with decreasing SiO_2 and increasing TiO_2 and Al_2O_3 concentrations, although the trends are poorly defined. A group of samples contain relatively high MgO of > 7% with rather limited variation in other major elements. They are classified as Group A samples. Group B samples are those having relatively high Na_2O content at a given MgO content. Group C samples have Na_2O, K_2O, and MnO distributing in larger ranges with MgO content extending to lower values of 4.5%. The Groups A and B samples define a positive LREE-HREE correlation, whereas the trend of Group C samples deviates to lower HREE values, implying petrogenetic differences. In the $^{87}Rb/^{86}Sr$-$^{87}Sr/^{86}Sr$ plot, Group A samples form an inverse trend below that defined by Groups B and C, indicating the involvement of at least two components in these samples. The low and high $^{87}Sr/^{86}Sr$ end-members are inferred to be mantle and crustal components, respectively. The crustal component, however, cannot be the wall rocks of the dikes for their high $^{87}Rb/^{86}Sr$ values, arguing against crustal contamination at shallow levels. This inference is supported by the $^{206}Pb/^{204}Pb$-$^{208}Pb/^{204}Pb$ plot, in which the wall rocks have $^{208}Pb/^{204}Pb$ ratio higher than that required for the crustal component. According, it is proposed that source contamination is responsible for the Sr and Pb isotopic features of LaiLai dikes. However, the nature of the contaminant needs to be further specified.

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臺灣西南部甲仙地區冷泉碳酸鹽之生物指標化合物與甲烷滲流古環境探討

Investigation of Biomarkers and Methane Seepage Paleoenvironments of Cold-Seep Carbonates in the Jiaxian Area, SW Taiwan

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摘　要

冷泉滲漏過程中發育而成的碳酸鹽岩稱之為冷泉碳酸鹽岩，是缺氧微環境下經由古菌與硫酸鹽還原菌互養作用而成。海底沉積物中的甲烷與孔隙水中硫酸根，經古菌和硫酸鹽還原菌的甲烷厭氧氧化作用(AOM)產生碳酸氫根，使得微環境中鹼度提高，促進碳酸鈣飽和並沉澱，形成自生性的碳酸鹽岩。冷泉碳酸鹽岩受控於甲烷通量、流體速率、沉積速率及生物擾動等因素影響，可做為海水、沉積物、海床環境、油氣徵與化學自營性生物群落交互作用的指標。臺灣西南部新生代地層中的冷泉碳酸鹽岩，紀錄著沉積盆地由張裂期過渡到前陸盆地發育期的甲烷逸氣事件；然而，對於甲烷氣滲流過程涉及之有機地球化學、不同產狀的冷泉碳酸鹽岩蘊含之環境意義，以及和生物地球化學間之交互作用等仍有待更多研究。本研究係針對高雄甲仙地區上新世早期鹽水坑頁岩層中的冷泉碳酸鹽岩與圍岩，進行有機物成份分析，以氣相層析質譜儀進行生物指標化合物組成鑑定，期待透過具有來源專一性和抗菌蝕能力的生物指標化合物，為古沉積環境解析提供解答。初步結果顯示：(1) 冷泉碳酸鹽岩的優勢烷烴分布於兩區間，分別為C_{16}~C_{18}(藻類來源)以及C_{24}~C_{27}(高等植物來源)，顯示形成甲烷的有機物為混合來源；(2) 陸源/水生正烷烴比值(TAR)為0.6，指示海源有機物比例大於陸源輸入；(3) Pr/n-C_{17}與Ph/n-C_{18}比值分析結果顯示有機物混和海相及陸相來源，環境指示為氧化還原過渡帶。本研究從有機地球化學觀點，探討高雄甲仙地區冷泉碳酸鹽岩的有機物來源及氧化還原條件，未來將鑑識冷泉碳酸鹽岩中的芳香烴和其他生物指標化合物並進行交互參照，為冷泉碳酸鹽岩之發育、環境或盆地演化提供更多解析資料。

關鍵字：甲仙、冷泉碳酸鹽岩、生物指標、甲烷滲漏、鹽水坑頁岩

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臺灣西南部泥火山之生物指標特徵及潛在噴發機制探討

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摘要

泥火山是沉積盆地、聚合邊緣和隱沒帶深層物質向上遷移的重要途徑，亦是甲烷排放的主要通道之一，可指示著地層下方蘊藏油氣藏，常伴生在斷層或褶皺軸附近。以臺灣西南部而言主要有四個泥火山分區，包含:觸口斷層泥火山、旗山斷層泥火山、古亭坑背斜區泥火山與海岸平原區泥火山。根據前人文獻得知滾水坪泥火山屬於古亭坑背斜泥火山，而部分學者認為應屬於海岸平原區泥火山，顯然對於泥火山的分區尚無共識。經由現地觀察，發現滾水坪泥火山噴口持續遷移，前人文獻指出為同一來源，惟有多個通道造就不同泥火山，泥質流體可反應來源地層和上湧過程的綜合資訊，本研究發現不同時期與不同噴口之滾水坪泥火山正烷烴分佈具顯著差異，而有機物來源對於泥火山活動的影響仍缺乏充分的討論，對於超壓流體積聚驅動泥火山活動或是構造主導著泥火山噴發，目前亦是懸而未決的問題。有鑑於此，本研究採集滾水坪、小滾水、養女湖泥火山之泥樣，利用索式萃取法萃取有機物，並使用氣相層析質譜儀鑑定生物指標化合物以瞭解其有機地球化學組成，藉由生物指標具有來源專一性及不易被風化降解的特性，能提供深部地層與流體之來源及化學組成資訊。結果顯示，滾水坪泥火山的新噴口樣品中 Pr/Ph~1.57 屬於氧化沉積環境，滾水坪泥火山舊噴口樣品 Pr/Ph~1.23 屬於氧化沉積環境;小滾水泥火山 Pr/Ph~1.36 屬氧化沉積環境，養女湖泥火山 Pr/Ph~2.28 亦屬氧化沉積環境，為探討時間與空間尺度上有機物成分變異，本研究從 2022 年至 2023 年持續對滾水坪泥火山進行成份分析，結果發現滾水坪泥火山的有機物來源似乎有二個來源，分別為以 C_{14} 正烷烴為優勢烷烴的來源與 C_{25} 正烷烴為優勢烷烴的來源，C_{23}-C_{31} 奇數烷烴優勢指示著非海相藻類來源。未來本研究將分析其他臺灣西南部泥火山之生物指標，結合無機地球化學分析結果與地下地質構造，釐清泥火山有機物來源，試圖為泥火山的來源和噴發機制提供更深入的解釋。

中文關鍵字:生物指標、泥火山、來源、有機地球化學
Keywords: Biomarker, Mud volcano, Origin, Organic chemistry

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大屯火山群黃鐵礦地球化學特徵對金礦床的成因隱示

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Geochemical Characteristics of Pyrite: Implications for Genesis of gold deposits in Tatun volcanic area, Taipei

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摘　要

黃鐵礦為地表最豐富的硫化物，廣泛分布於不同類型的熱液系統和成岩作用，其礦物學與地球化學特徵更是尋找金礦的重要指標。本研究聚焦於大屯火山硫磺子坪地區，鄰近據史載西班牙人開採的三重橋金礦。因此，我們利用掃描式電子顯微鏡(Scanning Electron Microscope; SEM)、電子能量散射分析(Energy-Dispersive x-ray Spectroscopy; EDS)以及雷射剝蝕感應耦合電漿質譜儀(Laser Ablation Inductively Coupled Plasma Mass Spectrometry; LA-ICP-MS)對該區域的鑽井岩心之黃鐵礦進行分析，並與金瓜石產出之黃鐵礦比較兩者礦物學與地球化學之特徵，進一步探討金礦存在之可能性。

本研究初步成果顯示，此岩心之黃鐵礦分布在深度 450-500 公尺處相對富集，產狀多為不規則團狀、塊狀，晶型呈現六面體與八面體，晶體大小約 10 ~100 微米(um)，且含有黃金 1.1-2.6 個重量百分數(wt%)。進一步研究將記錄晶型及黃金含量隨深度的變化，同時量測含金量最高的黃鐵礦之地球化學特徵，如 Fe/S，Co/Ni，S/Se，Te/Se 等元素比值，解釋該區域的成礦環境與流體來源。此外，黃金能以”不可見金(Invisible Gold)”的形式存在於硫化物中，包括奈米粒子與晶格取代兩種，透過 Au/As 比值可以指示黃金會以何種形式存在，並與金瓜石樣本比較，藉此了解成礦作用的機制與過程。最後，結合硫同位素數據辨別此區域黃鐵礦之成礦流體來源。綜上所述證據探討硫磺子坪存在金礦的可能性，以及提供成因上的指示意義。

關鍵字：黃鐵礦、金礦床、不可見金、大屯火山群

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中華民國地質學會與中華民國地球物理學會113年暨學術研討會 SP-297

以多元素、稀土元素及鉛同位素探討論卑南溪流域沉積物來源

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摘 要

天然示蹤劑，以其自然來源之地球化學組成去推估不同成分的來源。本研究以多元素、稀土元素以及鉛同位素作為天然示蹤劑，分析卑南溪流域，包含其支流大崙溪、鹿寮溪、鹿野溪以及其東部流域海岸山脈的沉積物化學組成，探討流域內不同水系中各成分的來源及分布。本研究蒐集了50個樣本，其中包含了沉積物、河中之懸浮沉積物以及土壤，這些樣本會先以連續萃取法處理，用意為去除其他相態之干擾，只取其殘餘相，再進行微波消化以及基質轉換，使用感應耦合電漿質譜儀量測微量元素、稀土元素以及鉛同位素；使用感應耦合電漿光譜儀量測主量元素以及濃度較高的微量元素。

根據儀器的分析結果，在主要以及微量元素上並無明顯的規則變化。稀土元素在經過上部大陸地殼正歸化後，並無明顯異常值，但根據稀土元素之圖譜可大致分為輕稀土富集以及無明顯富集兩類，而樣本種類為沉積物者大多有輕稀土富集的現象，懸浮沉積物則屬於無明顯富集，推測對於稀土元素來說可能產生了粒徑效應，單純以沉積物之稀土元素圖譜可以將位於東部之海岸山脈樣本與相較西部之其他樣本區隔開來，表示沉積物之來源不同推測與流經之地層差異有關。以稀土元素之比值作圖後可看出海岸山脈、主流以及支流三個不同端元的混合趨勢。

鉛同位素分析顯示，以鉛濃度作圖可發現懸浮沉積物的濃度明顯低於沉積物以及土壤，而海岸山脈沉積物又較其他沉積物樣本濃度低，以鉛同位素作圖也可明顯區分出沉積物以及懸浮沉積物也可大致區分海岸山脈以及其他樣本。主成分分析結果，第二主成分的正向較多屬於懸浮沉積物而負向則是沉積物，海岸山脈樣本主要分布在主成分分析的第四象限。

大多數的分析結果皆可區分卑南溪流域東西部合流沉積物來源的差異；以及沉積物和懸浮微粒的差異，推測可能受到粒徑大小之影響，後續研究或許可以先進行粒徑分析便可以得知更確切的結果。

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臺灣東北外海－棉花嶼的火山噴發類型與演化模式

Volcanic Eruption Types and Evolution Model of Mianhua Island, Northeast Offshore Taiwan

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摘　要

「棉花嶼」與彭佳嶼、花瓶嶼統稱為北方三島，為臺灣北部火山活動帶中分布最北的成員，棉花嶼的地貌也未受到人為破壞，火山岩未受到風化保存良好，為探討玄武岩火山噴發行為與模式的良好題材。然而，過去棉花嶼的前人研究多著重於地球化學與放射性定年之研究，鮮少探討火山噴發行為與演化模式之議題。鑑此，本研究首先透過高解析度航照圖進行地形分析，再透過野外調查火山岩之產狀與分佈並進行岩相分析；配合前人研究之資料進行彙整，嘗試重建棉花嶼的火山島噴發類型與演化模式。

棉花嶼的西北部地形平緩，海岸邊有海階發育；東南部地形高聳，有三個近似半圓型的地形分布於此處，同時海岸呈現陡峭且多大岩塊散佈。島上的火山岩可劃分為 5 種不同的岩相，分別為：(1)pTB:橙玄武玻璃化之玻璃質火山灰，偶夾火山角礫岩。掏選度中等至佳，具有正、雙礫級層、平行紋理與低角度交錯層之特徵。為(2)aaL:具有三明治構造(sandwich structure)、斜坡構造(ramping structure)之玄武岩質熔岩流。(3)phL:具有繩狀構造、水平氣孔層之玄武岩質熔岩流。(4)spL：掏選度中至差，具氣孔之不規則火山角礫。(5)Dy:具氣泡構造、冷卻邊緣之侵入岩脈。棉花嶼最底部之層序以的 pTB 岩相為主，;Dy 岩相則截切穿越前兩個層序。

噴發中心位於棉花嶼東南側，噴發型態由淺水轉至陸上環境，噴發強度逐漸

下降至歇止，演化過程如下：早期的 Surtseyan 噴發產生大量低濃度火山碎屑密度流的 pTB 相火山噴發物，形成棉花嶼的基底。隨相對海水面低於火山噴發口，火山轉變為溢流式的夏威夷式噴發為主，產生 aaL、phL 相熔岩流堆積物並形成島的主體；同時在東南側形成 3 個噴濺火山錐(spatter cone)由 spL 岩相堆積物組成。隨時序演進，小規模的噴發活動與岩漿通道(conduit)上湧，使火山體發生垮塌，產生現今棉花嶼東南側的火山垮塌地形。

關鍵字:
棉花嶼、瑟西洋式噴發、夏威夷式噴發、渣狀熔岩流、繩狀熔岩流
Mianhua Island, Surtseyan type eruption, Hawaiian type eruption, a’a lava flows, Pāhoehoe lava flows

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台灣西南部河川化學風化作用對於二氧化碳排放的控制機制及通量

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摘　要

化學風化為碳循環中的主要作用之一，岩層中的矽酸鹽及碳酸鹽與環境中的酸類反應，如碳酸、硫酸，將對二氧化碳的消耗與釋放產生不同影響。大氣中的二氧化碳經與水結合形成碳酸後，藉矽酸鹽風化反應而消耗；然而在造山地帶如台灣西南部麓山帶，高聳陡峭的地勢與持續的抬升運動，使地層不斷出露大量新鮮面，其中富含的硫化礦物，特別是黃鐵礦，氧化後與水結合產生硫酸，經風化碳酸鹽後，產生的陽離子與碳酸氫根在碳酸鈣補償時間(萬年)尺度以上，則會間接造成二氧化碳的淨釋放。相較於碳酸，硫酸對於地層中的碳酸鹽反應速率更快，風化作用更具優勢，然而硫酸風化的貢獻在現有的評估及二氧化碳通量計算方法中，不論是在空間及時間上皆需更多觀測資料來完備。由於岩石風化會對河水化學造成直接影響，故可透過河水溶解離子分析來反推風化反應的進行。本研究針對台灣西南部六條主要河川（八掌溪、急水溪、鹽水溪、後堀溪、二仁溪、高屏溪）橫跨乾、濕季數個時間點進行時間序列採樣，以評估不同季節、降雨、溫度等環境條件下，台灣西南部河川風化作用對於碳排的控制因素及影響。採集後樣本由ICP-OES測得主要離子濃度、以滴定法量測溶解無機碳（DIC），由化學式及河川流量資料進一步計算碳酸及硫酸造成的二氧化碳通量及風化速率。此外，亦透過量測硫同位素比值，評估自然源或人為源硫酸的貢獻比例。計算結果顯示台灣西南部的河水溶解物質中碳酸鹽約占近八成、矽酸鹽約占兩成；總體物質約有四成來自硫酸作用，且主要為碳酸鹽礦物的風化。濕季流量越大，硫同位素比值越趨近黃鐵礦端元，計算得出的硫酸風化比例亦相應提升約1.2 至 2.3倍，支持由硫化礦物產生硫酸進而造成風化的推論。在碳酸鈣補償時間尺度以上，台灣西南部風化作用在大量硫酸的參與下，二氧化碳排放通量估算介於1.16×10^{6}及2.11×10^{10} mol yr^{-1} 之間，各採樣點在乾濕季的通量差異可達數倍至數千倍。

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評估東亞季風帶極端氣候條件下化學風化源季節性變異特性

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摘　要

地表的化學風化過程會對長時間尺度的碳循環有所影響。流域化學風化源主要以矽酸鹽類(Silicate)及碳酸鹽類(Carbonate)為主，化學風化產生及消耗之碳酸量，可進一步計算大氣二氧化碳的淨消耗或淨排放。本研究將在東亞季風帶中溫暖潮濕的台灣西南部重要河川及寒冷乾燥的青海湖地區，依當地降雨變化進行時間序列採樣，以探討兩個截然不同氣候條件下所發生的化學風化作用。在實驗流程設計，量測水樣pH值及滴定分析碳酸氫根濃度後，再由感應耦合電漿發射光譜儀進行元素分析，接著透過鍶元素純化，以多接收器感應耦合電漿質譜儀測量$^{87}Sr/^{86}Sr$同位素比值。最後由風化來源比例及河川流量，推算二氧化碳吸收與排放量相對通量（R值），探討其化學風化對長時間尺度碳循環之影響。透過化學及同位素資料，本研究判識風化來源並分析其季節性變化。研究成果顯示：在台灣西南部河水化學組成呈現季節性的差異，乾濕季化學元素離子濃度比例約相差三至五成，乾季的$^{87}Sr/^{86}Sr$比值整體也較濕季來的高，風化來源以碳酸鹽比例相對較高。R值平均都大於1，且濕季較乾季的值大約兩倍，表明其環境在長時間尺度下為碳排為主，且濕季作用較乾季強。青海湖地區在化學元素離子濃度趨勢與台灣西南部類似。R平均值大多大於1，且和台灣西南部相似亦有季節性差別。不同的是青海湖R值較台灣西南部大，但乾濕季R值相差並不像台灣西南部來的劇烈，僅相差三成左右。這樣的差異主要與兩者平均降雨量、河川流量、溫度等氣候變因有關，而對於二氧化碳的收支是碳匯亦或為碳排，相關結果將進一步釐清風化作用對於環境中二氧化碳的影響。

關鍵字：台灣西南部溪流、青海湖、化學風化源、二氧化碳、感應耦合電漿發射光譜儀(ICP-OES)、多接收器感應耦合電漿質譜儀(MC-ICP-MS)

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