出國報告（出國類別：開會）

參加國際能源地球化學會議

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出國期間：114.07.05-114.07.14
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出國報告目錄

摘要

因應政府訂定「2050年淨零碳排」的目標，參加2025年由歐洲地球化學協會(European Association of Geochemistry，EAG)與地球化學學會(Geochemistry Society)舉辦的地球化學協會會議(Goldschmidt 2025)，在捷克共和國首都布拉格舉行。

大會議程涵蓋主題相當多元，皆以地球化學為出發點，牽涉研究領域相當廣泛。參與議程聚焦於地球化學應用於碳捕集與封存(Geochemistry of CCS)、地球化學油氣探勘、陸地及海洋風化訊號及紀錄、化學風化及河川沉積作用、二氧化碳移除(CDR)等主要議題。在眾多議題中，聚焦於二氧化碳礦化與溶解封存、礦化與溶解潛能估算、氫能及頁岩油氣探勘、沉積物與氣候變遷等議題，對本公司近年積極推廣減碳、能源轉型非常具有參考價值，透過會議內容以獲取更多新穎技術與資訊，如人工智慧(AI)工具的應用，並了解國際在執行 CCS 的成果及相關研究走向。

參加會議期望在碳封存技術發展獲取國外新知，借鏡國外成功案例來促進國內減碳工程推動，對於本公司能源轉型、減緩氣候暖化、改善環境與民眾健康有將有正面影響。

一、 出國目的：

因應政府訂定「2050年淨零碳排」的目標，了解地球化學於碳封存監測方法與相關實務，及地球化學發展方向，參加2025年由歐洲地球化學協會(European Association of Geochemistry，EAG)與地球化學學會(Geochemistry Society)舉辦的地球化學協會會議(Goldschmidt 2025)，於114年7月5日至7月14日在捷克共和國首都布拉格舉行，地點於布拉格會議中心(Prague Congress Centre)，大會議程涵蓋主題相當多元，以本公司CCS 業務為優先參與議題，在推廣減碳、能源轉型方面將有助益，透過會議內容(論文宣讀、專題研討、壁報展示等)以獲取更多技術與資訊。

依本公司探採研究所研究業務，聚焦的主題為地球資源與能源(Earth Resources and Energy)，其包含了地球化學於 CCS 之應用研究，如二氧化碳與油氣水岩的反應、礦化封存潛能評估、海洋鹼度增強(Ocean Alkalinity Enhancement, OAE)或其他二氧化碳移除(Carbon Dioxide Removal, CDR)之方法、化學風化與沉積物來源研究等子議題，經由這些議題來獲取新的技術資訊，包含 AI 工具應用等，以作為本公司在能源轉型過程的參考依據，且於後續的二氧化碳灌注作業、監測作業與移棲模擬，提供更多考量。

其他如地表與氣候衝擊(Earth Surface Processes and Their Climatic Impacts)主題中，陸地及海洋風化訊號及紀錄的子議題 (Terrestrial and marine weathering signals and environmental records in continental margins)，研究有機碳來源、利用稀土元素(Rare Earth Element, REE)同位素探究沉積物來源及古環境變化，碳酸鹽與矽酸鹽的化學風化(Chemical Weathering)過程。在地球化學油氣探勘領域上，非傳統油氣探勘及盆地模擬預測，如頁岩油或是蘊藏於頁岩中的氫能，抑或是未來能源轉型的方向。

二、 會議過程：

本次會議參與過程及議題時程，詳如下表：

日期	上午	下午	晚間
7/5(六)	-	-	桃園機場出發
7/6(日)	抵達捷克(布拉格-哈維爾機場)	大會報到手續	Welcome Icebreaker Reception
7/7(一)	議題：Geochemistry of carbon capture and storage(CCS)	議題：Interfacial Geochemistry	(壁報論文) Posters
7/8(二)	議題：Terrestrial and marine weathering signals and environmental records in continental margins		(壁報論文) Posters
7/9(三)	議題：Chemistry and Dynamics of Earth's Interior		(壁報論文) Posters
7/10(四)	議題：Carbon dioxide removal (CDR) from the atmosphere		(壁報論文) Posters
7/11(五)	議題：Chemical weathering and fluvial sedimentary processes	議題：Earth Resources and Energy	
7/12(六)	自由參訪		
7/13(日)	捷克(布拉格-哈維爾機場)出發	-	-
7/14(一)	抵達桃園機場		

地球化學協會會議的議程首日以現場報到及破冰(Welcome Icebreaker Reception)為主要議程(圖 1)。除主辦單位歐洲地球化學協會(EAG)及地球化學協會介紹，尚有眾多國外儀器廠商及贊助商蒞臨，並設有攤位解說人員進行技術服務或儀器設備說明。其他如 Elsevier 與 Springer Nature 期刊廠商也有進行刊物展示。

圖 1 Goldschmidt 2025首日活動於布拉格會議中心舉行

議程期間所參與的議題眾多，共彙整以下五項主題：地球化學於二氧化碳捕捉及封存(CCS)應用、地球化學油氣探勘、化學風化及河川沉積作用，地表作用與氣候衝擊暨陸地及海洋風化訊號及紀錄，以及二氧化碳移除(CDR)等，另包含了壁報論文和 AI 工具的應用(GeoGPT)。以下進行綜合說明：

1. 地球化學應用於 CCS：

CCS 相關議題聚焦於二氧化碳的礦化封存及溶解封存。在礦化封存議題上，整理以下三個案例供參考：

1.1 冰島 Carbfix Project 案例(圖 2)

將二氧化碳與水混合後注入中生代玄武岩等基性岩石(mafic rock)中，利用基性岩石礦物內的鐵鎂離子與二氧化碳水溶液進行反應，產生碳酸鹽沉澱以達到礦化封存之目的。要評估礦化效率，通常於注入過程加入試蹤劑(Tracer)，如 SF_6、NS、^{14}C，比較注入前後的試蹤劑濃度變化；而較新的方法採用固有試蹤劑(Inherent Tracer)，即二氧化碳本身與惰性氣體(noble gas)。二氧化碳含有^{13}C 與^{12}C，而^{12}C 在特定溫度(>200℃)下易進入碳酸鹽中，剩餘的為^{13}C，比較^{13}C 與^{12}C 的比值與 CO_2與^{3}He 的差異即可得知礦化封存效率。

本案例屬於地質上的最終封存方法－礦化封存，以玄武岩或橄欖岩等基性或火成岩為注入地層，利用其礦物特性加速二氧化碳封存於岩石內，亦可作為地下鹽水層以外的選項。

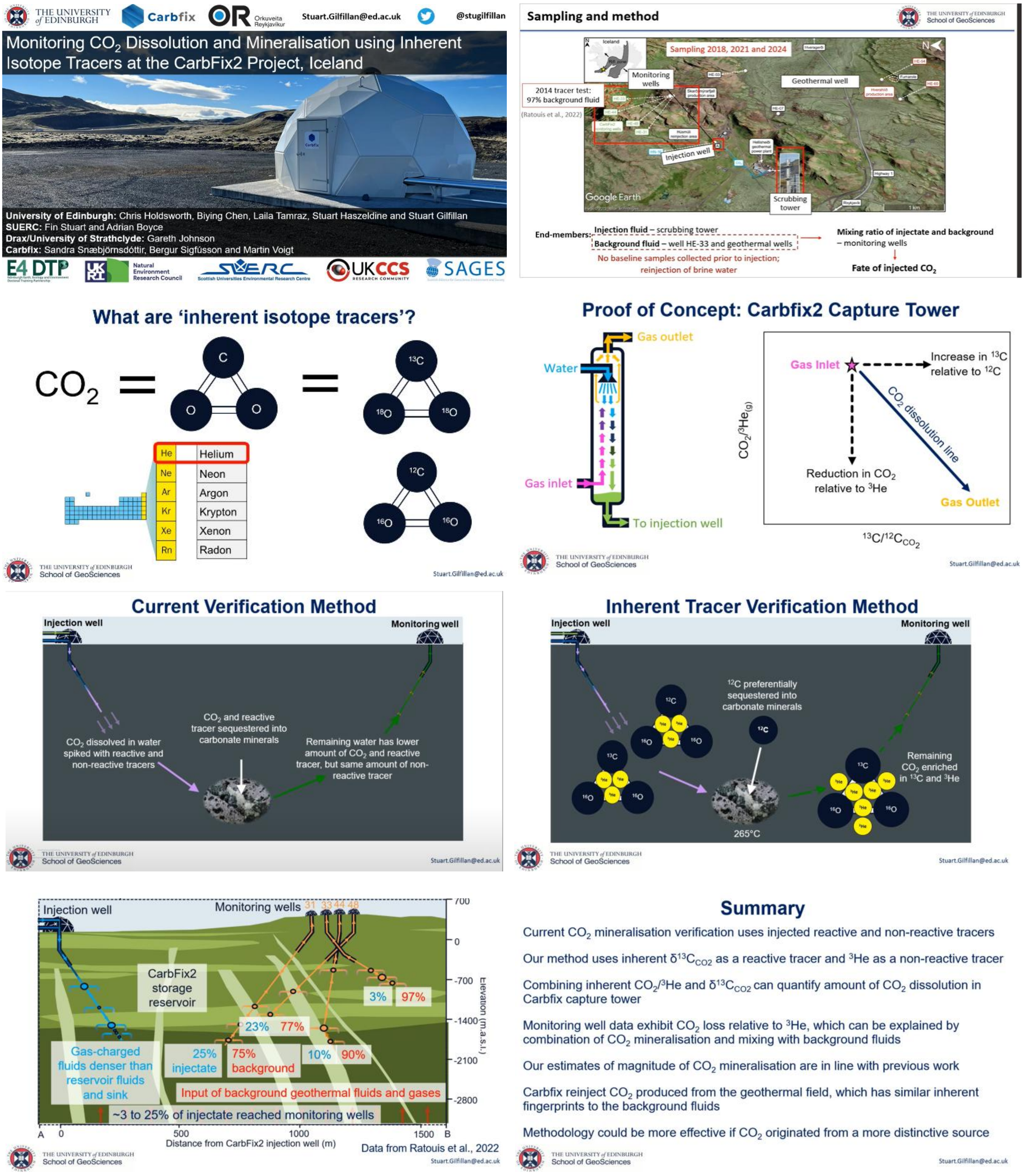
1.2 沙烏地阿拉伯的吉讚(Jizan) 礦化封存先導試驗(圖 3)

同樣將二氧化碳與水混合後，透過鑽井注入玄武岩層，並添加試蹤劑。注入後，觀測溶解無機碳(Dissolved Inorganic Carbon, DIC)與 pH 值變化、流體內離子濃度隨時間變化(DIC/Mg/Ca/Si)、試蹤劑濃度隨時間變化，推算礦化封存效率。此法可提供未來於二氧化碳注入過程及後續監測作業的參考。

1.3 加拿大魁北克(Quebec)雷納德鑽石礦場(Renard Mine)(圖 4)

利用礦場開採出來的慶伯利岩(Kimberlite)，經過處理後製成能促進礦化的材料(Feedstock)。礦化材料的特性，無論是岩石或礦物，以非產生酸性(Non-acid generating)、富含鎂鐵鈣等陽離子，且容易化學風化並釋出陽離子、促進二氧化碳礦化、材料表面積大等為準則。分析並評估由各礦區開採出的慶伯利岩在二氧化碳礦化封存的潛能優劣。

未來可尋找具有二氧化碳礦化潛能材料進行研究，因地質封存最終期望是可將二氧化碳固定於岩石礦物內，減少大氣的二氧化碳濃度，進一步延緩地球暖化與氣候變遷，



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Monitoring CO_2 Dissolution and Mineralisation using Inherent Isotope Tracers at the CarbFix2 Project, Iceland

University of Edinburgh: Chris Holdsworth, Biying Chen, Laila Tamraz, Stuart Haszeldine and Stuart Gilfillan
SUERC: Fin Stuart and Adrian Boyce
Drax/University of Strathclyde: Gareth Johnson
Carbfix: Sandra Snæbjörnsdóttir, Bergur Sigfússon and Martin Voigt

Sampling and method

2014 tracer test: 97% background fluid (Ratouis et al., 2022)

End-members: **Injection fluid** – scrubbing tower; **Background fluid** – well HE-33 and geothermal wells → **Mixing ratio of injectate and background – monitoring wells** → **Fate of injected CO_2**

No baseline samples collected prior to injection; reinjection of brine water

What are 'inherent isotope tracers'?

CO_2 = C, O, O = ^{13}C, ^{18}O, ^{18}O / ^{12}C, ^{16}O, ^{16}O

He	Helium
Ne	Neon
Ar	Argon
Kr	Krypton
Xe	Xenon
Rn	Radon

Proof of Concept: Carbfix2 Capture Tower

Current Verification Method

CO_2 dissolved in water spiked with reactive and non-reactive tracers

CO_2 and reactive tracer sequestered into carbonate minerals

Remaining water has lower amount of CO_2 and reactive tracer, but same amount of non-reactive tracer

Inherent Tracer Verification Method

^{12}C preferentially sequestered into carbonate minerals

Remaining CO_2 enriched in ^{13}C and ^3He

Gas-charged fluids denser than reservoir fluids and sink

Input of background geothermal fluids and gases

~3 to 25% of injectate reached monitoring wells

Data from Ratouis et al., 2022

Summary

Current CO_2 mineralisation verification uses injected reactive and non-reactive tracers

Our method uses inherent $\delta^{13}C_{CO_2}$ as a reactive tracer and ^3He as a non-reactive tracer

Combining inherent $CO_2/^3He$ and $\delta^{13}C_{CO_2}$ can quantify amount of CO_2 dissolution in Carbfix capture tower

Monitoring well data exhibit CO_2 loss relative to ^3He, which can be explained by combination of CO_2 mineralisation and mixing with background fluids

Our estimates of magnitude of CO_2 mineralisation are in line with previous work

Carbfix reinject CO_2 produced from the geothermal field, which has similar inherent fingerprints to the background fluids

Methodology could be more effective if CO_2 originated from a more distinctive source

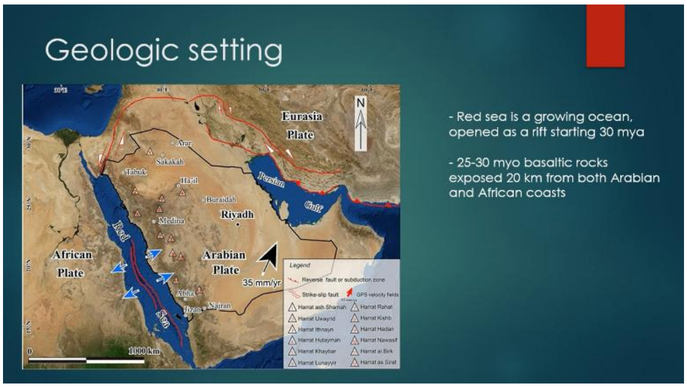
圖 2 冰島 Carbfix Project 案例研究

The Jizan (Southwest Saudi Arabia) subsurface CO_2 mineral storage pilot project: Update and outlook

Eric H. Oelkers[1,3], Mouadh Addassi[3], Abdirizak Omar[3], Abdulkader M. Afifi[3], Hussein Hoteit[3], Thomas Finkbeiner[3], Niccolo Menegoni[3], Antoine Delaunay[3], Jakub Fedorik[2], Zeyad T. Ahmed[2], Noushad Kunnummal[2], Sigurdur R. Gislason[1], Grimur Bjornsson[4], Davide Berno[3] Serguey V. Arkadakskiy[2]

1. Institute of Earth Sciences, University of Iceland, Sturlugötur 7, 102 Reykjavík, Iceland
2. Saudi Arabian Oil Company, Dahahran, Saudi Arabia
3. Ali I. Al-Naimi Petroleum Engineering Research Center, KAUST, Saudi Arabia
4. Warm Arctic ehf, Skjolbraut 22, 200 Kopagovur Iceland

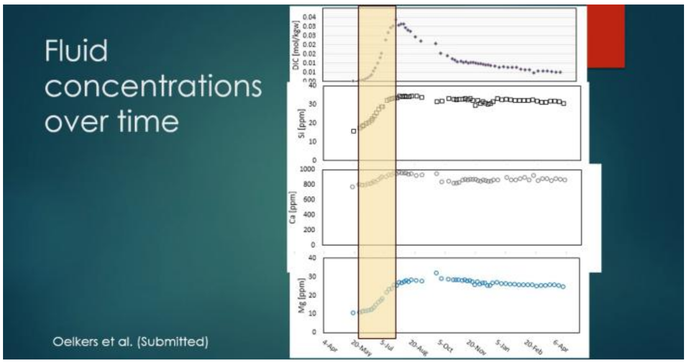
JULY 2025



Geologic setting

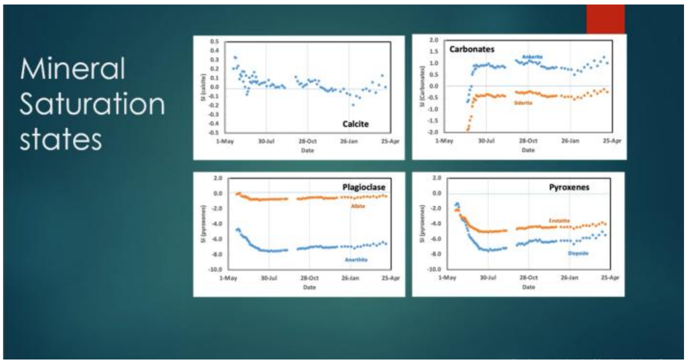
- Red sea is a growing ocean, opened as a rift starting 30 mya

- 25-30 myo basaltic rocks exposed 20 km from both Arabian and African coasts



Fluid concentrations over time

Oelkers et al. (Submitted)



Mineral Saturation states

圖 3 沙烏地阿拉伯的吉讚(Jizan) 礦化封存先導試驗

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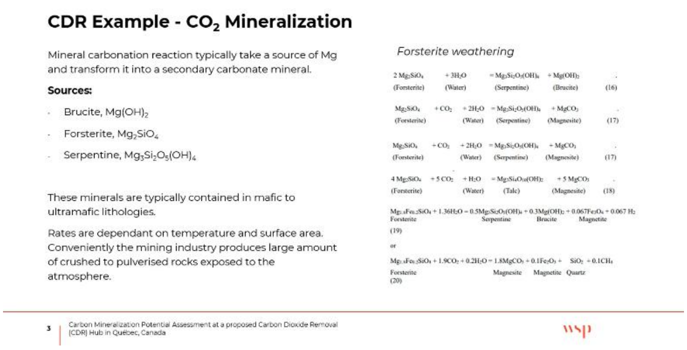
Carbon Mineralization Potential Assessment at a proposed Carbon Dioxide Removal (CDR) Hub in Québec, Canada

Bart De Baere[1], **Julien Declercq**[1], Rhys John Savage[2]
(1) WSP, (2) Isometric

Date: 7th of July 2025



CDR Example - CO_2 Mineralization

Mineral carbonation reaction typically take a source of Mg and transform it into a secondary carbonate mineral.

Sources:

- Brucite, $Mg(OH)_2$
- Forsterite, Mg_2SiO_4
- Serpentine, $Mg_3Si_2O_5(OH)_4$

These minerals are typically contained in mafic to ultramafic lithologies.

Rates are dependant on temperature and surface area. Conveniently the mining industry produces large amount of crushed to pulverised rocks exposed to the atmosphere.

Forsterite weathering

$$\underset{\text{(Forsterite)}}{2\,Mg_2SiO_4} + \underset{\text{(Water)}}{3H_2O} = \underset{\text{(Serpentine)}}{Mg_3Si_2O_5(OH)_4} + \underset{\text{(Brucite)}}{Mg(OH)_2} \quad (16)$$

$$\underset{\text{(Forsterite)}}{Mg_2SiO_4} + CO_2 + \underset{\text{(Water)}}{2H_2O} = \underset{\text{(Serpentine)}}{Mg_3Si_2O_5(OH)_4} + \underset{\text{(Magnesite)}}{MgCO_3} \quad (17)$$

$$\underset{\text{(Forsterite)}}{Mg_2SiO_4} + CO_2 + \underset{\text{(Water)}}{2H_2O} = \underset{\text{(Serpentine)}}{Mg_3Si_2O_5(OH)_4} + \underset{\text{(Magnesite)}}{MgCO_3} \quad (17)$$

$$\underset{\text{(Forsterite)}}{4\,Mg_2SiO_4} + 5\,CO_2 + \underset{\text{(Water)}}{H_2O} = \underset{\text{(Talc)}}{Mg_3Si_4O_{10}(OH)_2} + \underset{\text{(Magnesite)}}{5\,MgCO_3} \quad (18)$$

$$\underset{\text{Forsterite}}{Mg_{1.8}Fe_{0.2}SiO_4} + 1.36H_2O = \underset{\text{Serpentine}}{0.5Mg_3Si_2O_5(OH)_4} + \underset{\text{Brucite}}{0.3Mg(OH)_2} + \underset{\text{Magnetite}}{0.067Fe_3O_4} + 0.067\ H_2$$

(19)

or

$$\underset{\text{Forsterite}}{Mg_{1.8}Fe_{0.2}SiO_4} + 1.9CO_2 + 0.2H_2O = \underset{\text{Magnesite}}{1.8MgCO_3} + \underset{\text{Magnetite}}{0.1Fe_2O_3} + \underset{\text{Quartz}}{SiO_2} + 0.1CH_4$$

(20)

3 | Carbon Mineralization Potential Assessment at a proposed Carbon Dioxide Removal (CDR) Hub in Québec, Canada

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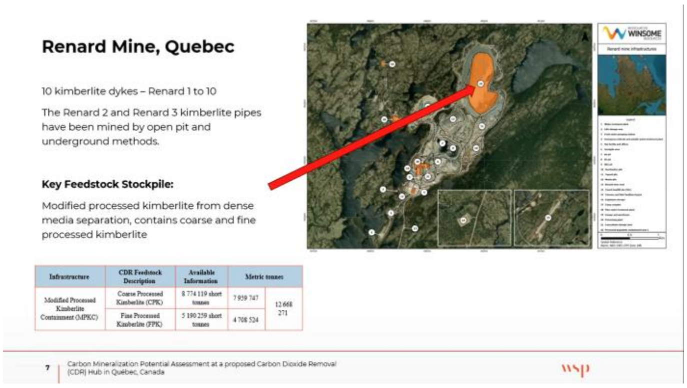

Renard Mine, Quebec

10 kimberlite dykes – Renard 1 to 10

The Renard 2 and Renard 3 kimberlite pipes have been mined by open pit and underground methods.

Key Feedstock Stockpile:

Modified processed kimberlite from dense media separation, contains coarse and fine processed kimberlite

Infrastructure	CDR Feedstock Description	Available Information	Metric tonnes	
Modified Processed Kimberlite Containment (MPKC)	Coarse Processed Kimberlite (CPK)	8 774 119 short tonnes	7 959 747	12 668 271
	Fine Processed Kimberlite (FPK)	5 190 259 short tonnes	4 708 524	

7 | Carbon Mineralization Potential Assessment at a proposed Carbon Dioxide Removal (CDR) Hub in Québec, Canada

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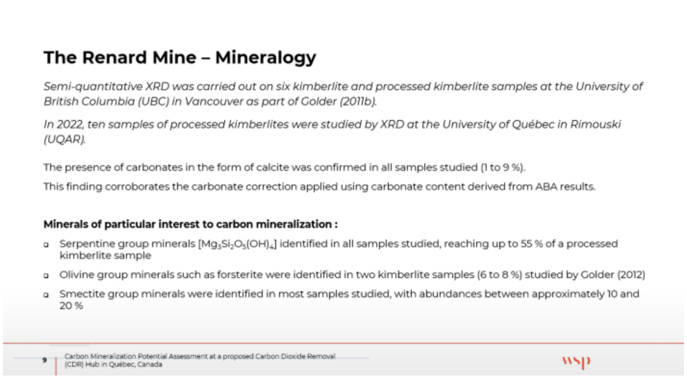

The Renard Mine – Mineralogy

Semi-quantitative XRD was carried out on six kimberlite and processed kimberlite samples at the University of British Columbia (UBC) in Vancouver as part of Golder (2011b).

In 2022, ten samples of processed kimberlites were studied by XRD at the University of Québec in Rimouski (UQAR).

The presence of carbonates in the form of calcite was confirmed in all samples studied (1 to 9 %).

This finding corroborates the carbonate correction applied using carbonate content derived from ABA results.

Minerals of particular interest to carbon mineralization :

- Serpentine group minerals [$Mg_3Si_2O_5(OH)_4$] identified in all samples studied, reaching up to 55 % of a processed kimberlite sample
- Olivine group minerals such as forsterite were identified in two kimberlite samples (6 to 8 %) studied by Golder (2012)
- Smectite group minerals were identified in most samples studied, with abundances between approximately 10 and 20 %

9 | Carbon Mineralization Potential Assessment at a proposed Carbon Dioxide Removal (CDR) Hub in Québec, Canada

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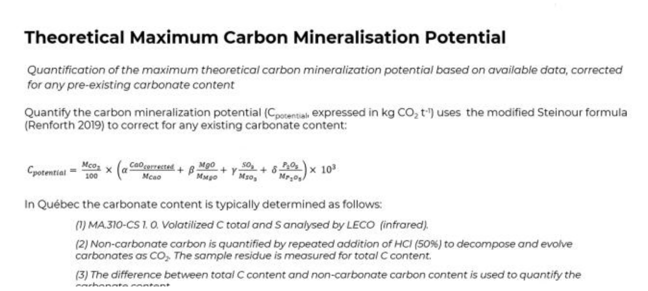


Theoretical Maximum Carbon Mineralisation Potential

Quantification of the maximum theoretical carbon mineralization potential based on available data, corrected for any pre-existing carbonate content

Quantify the carbon mineralization potential ($C_{potential}$, expressed in kg CO_2 t^{-1}) uses the modified Steinour formula (Renforth 2019) to correct for any existing carbonate content:

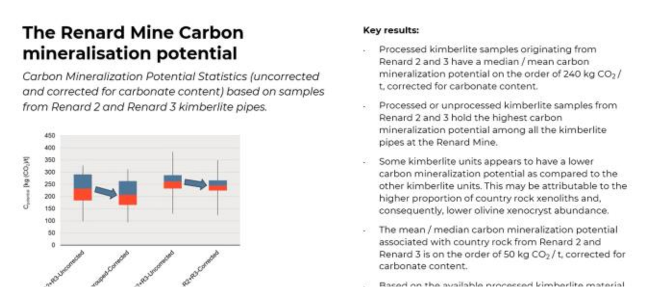
$$C_{potential} = \frac{M_{CO_2}}{100} \times \left(\alpha \frac{CaO_{corrected}}{M_{CaO}} + \beta \frac{MgO}{M_{MgO}} + \gamma \frac{SO_3}{M_{SO_3}} + \delta \frac{P_2O_5}{M_{P_2O_5}}\right) \times 10^3$$

In Québec the carbonate content is typically determined as follows:

(1) MA.310-CS 1. 0. Volatilized C total and S analysed by LECO (infrared).

(2) Non-carbonate carbon is quantified by repeated addition of HCl (50%) to decompose and evolve carbonates as CO_2. The sample residue is measured for total C content.

(3) The difference between total C content and non-carbonate carbon content is used to quantify the carbonate content.



The Renard Mine Carbon mineralisation potential

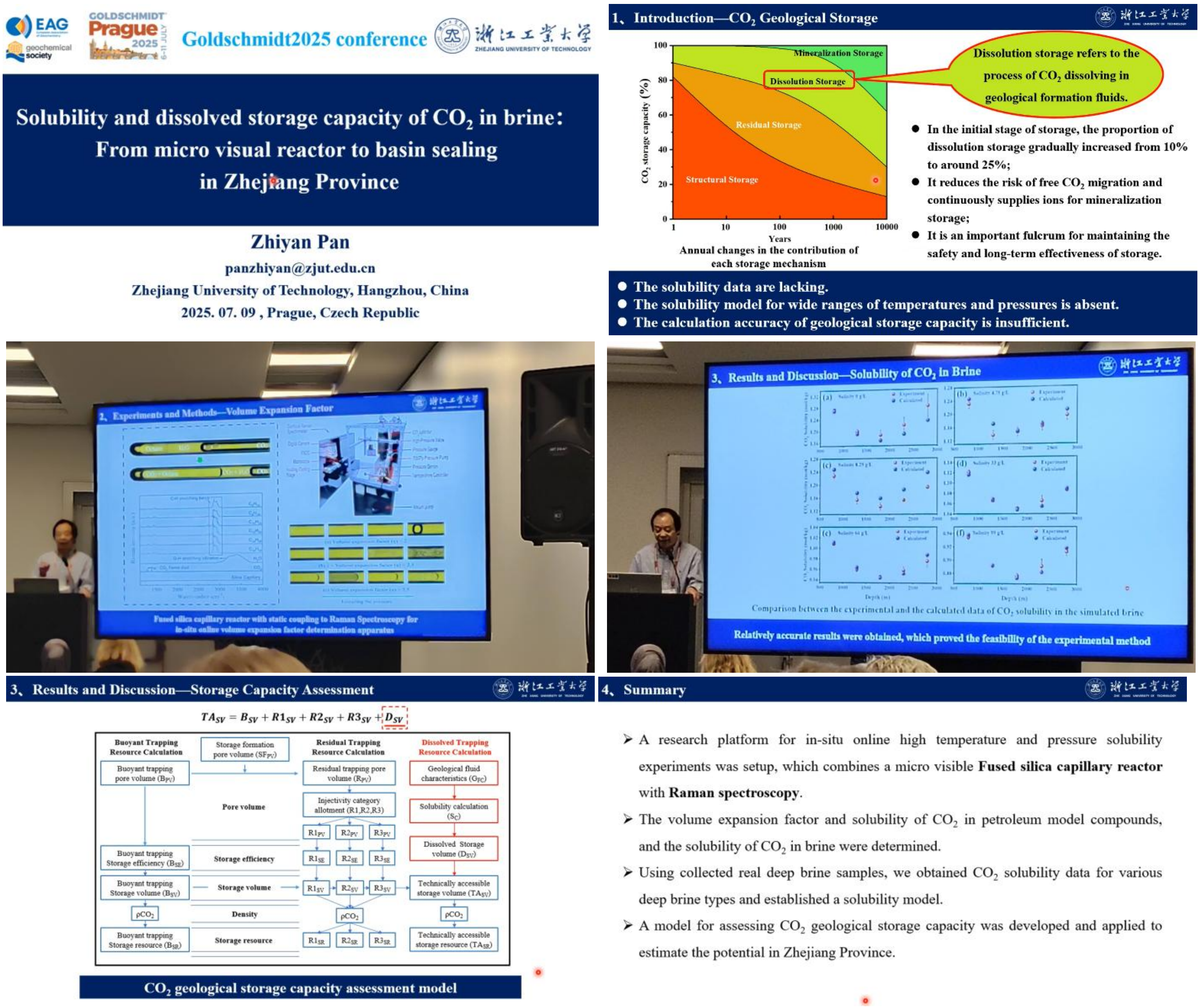
Carbon Mineralization Potential Statistics (uncorrected and corrected for carbonate content) based on samples from Renard 2 and Renard 3 kimberlite pipes.

Key results:

- Processed kimberlite samples originating from Renard 2 and 3 have a median / mean carbon mineralization potential on the order of 240 kg CO_2 / t, corrected for carbonate content.
- Processed or unprocessed kimberlite samples from Renard 2 and 3 hold the highest carbon mineralization potential among all the kimberlite pipes at the Renard Mine.
- Some kimberlite units appears to have a lower carbon mineralization potential as compared to the other kimberlite units. This may be attributable to the higher proportion of country rock xenoliths and, consequently, lower olivine xenocryst abundance.
- The mean / median carbon mineralization potential associated with country rock from Renard 2 and Renard 3 is on the order of 50 kg CO_2 / t, corrected for carbonate content.
- Based on the available processed kimberlite material

圖 4 加拿大魁北克(Quebec)雷納德鑽石礦場(Renard Mine)案例研究

在二氧化碳溶解封存的議題上(圖 5)，因普遍缺乏二氧化碳於鹽水層(Saline/Brine)的溶解度，國外研究中透過實驗方式建立溶解度模型以預測深部鹽水層內的二氧化碳溶解度，並計算溶解封存量，值得未來進行模擬研究的參照。



Goldschmidt2025 conference

Solubility and dissolved storage capacity of CO_2 in brine: From micro visual reactor to basin sealing in Zhejiang Province

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2025. 07. 09 , Prague, Czech Republic

1、Introduction—CO_2 Geological Storage

Annual changes in the contribution of each storage mechanism

Dissolution storage refers to the process of CO_2 dissolving in geological formation fluids.

- In the initial stage of storage, the proportion of dissolution storage gradually increased from 10% to around 25%;
- It reduces the risk of free CO_2 migration and continuously supplies ions for mineralization storage;
- It is an important fulcrum for maintaining the safety and long-term effectiveness of storage.

- The solubility data are lacking.
- The solubility model for wide ranges of temperatures and pressures is absent.
- The calculation accuracy of geological storage capacity is insufficient.

2、Experiments and Methods—Volume Expansion Factor

Fused silica capillary reactor with static coupling to Raman Spectroscopy for in-situ online volume expansion factor determination apparatus

3、Results and Discussion—Solubility of CO_2 in Brine

Comparison between the experimental and the calculated data of CO_2 solubility in the simulated brine

Relatively accurate results were obtained, which proved the feasibility of the experimental method

3、Results and Discussion—Storage Capacity Assessment

$$TA_{SV} = B_{SV} + R1_{SV} + R2_{SV} + R3_{SV} + D_{SV}$$

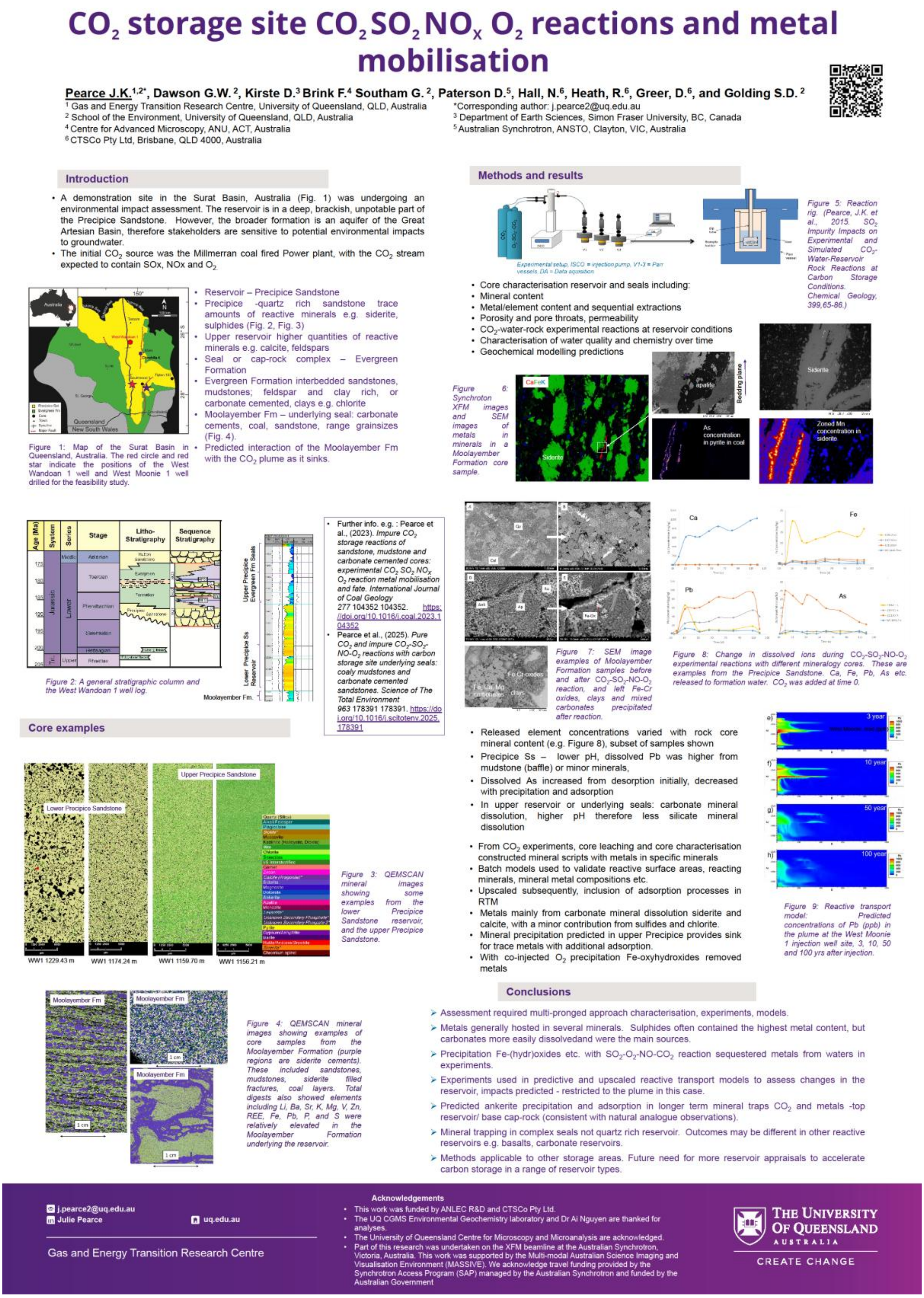
CO_2 geological storage capacity assessment model

4、Summary

- ➢ A research platform for in-situ online high temperature and pressure solubility experiments was setup, which combines a micro visible **Fused silica capillary reactor** with **Raman spectroscopy**.
- ➢ The volume expansion factor and solubility of CO_2 in petroleum model compounds, and the solubility of CO_2 in brine were determined.
- ➢ Using collected real deep brine samples, we obtained CO_2 solubility data for various deep brine types and established a solubility model.
- ➢ A model for assessing CO_2 geological storage capacity was developed and applied to estimate the potential in Zhejiang Province.

圖 5 二氧化碳溶解封存議題

另外在灌注二氧化碳過程，也需要考慮灌注氣體的成分(圖 6)。因灌注的氣體來源可能來自不同的產業，其不只是含有二氧化碳，也會有其他氣體混雜，需要考慮注入氣體對地下水及岩石的影響。可採用研究方法如岩芯(儲層/封阻層)特性、分析礦物組成、金屬元素 (Ca/Fe/Pb/As)移動性、地層孔隙度/滲透率、CO_2與水岩反應、分析水質特性、透過地化模型預測等方式，以作為二氧化碳監測作業的研究範疇。



CO_2 storage site CO_2 SO_2 NO_x O_2 reactions and metal mobilisation

Pearce J.K.[1,2*], Dawson G.W.[2], Kirste D.[3] Brink F.[4] Southam G.[2], Paterson D.[5], Hall, N.[6], Heath, R.[6], Greer, D.[6], and Golding S.D.[2]

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Introduction

- A demonstration site in the Surat Basin, Australia (Fig. 1) was undergoing an environmental impact assessment. The reservoir is in a deep, brackish, unpotable part of the Precipice Sandstone. However, the broader formation is an aquifer of the Great Artesian Basin, therefore stakeholders are sensitive to potential environmental impacts to groundwater.
- The initial CO_2 source was the Millmerran coal fired Power plant, with the CO_2 stream expected to contain SOx, NOx and O_2.

Figure 1: Map of the Surat Basin in Queensland, Australia. The red circle and red star indicate the positions of the West Wandoan 1 well and West Moonie 1 well drilled for the feasibility study.

- Reservoir – Precipice Sandstone
- Precipice -quartz rich sandstone trace amounts of reactive minerals e.g. siderite, sulphides (Fig. 2, Fig. 3)
- Upper reservoir higher quantities of reactive minerals e.g. calcite, feldspars
- Seal or cap-rock complex – Evergreen Formation
- Evergreen Formation interbedded sandstones, mudstones; feldspar and clay rich, or carbonate cemented, clays e.g. chlorite
- Moolayember Fm – underlying seal: carbonate cements, coal, sandstone, range grainsizes (Fig. 4).
- Predicted interaction of the Moolayember Fm with the CO_2 plume as it sinks.

Figure 2: A general stratigraphic column and the West Wandoan 1 well log.

- Further info. e.g. : Pearce et al., (2023). *Impure CO_2 storage reactions of sandstone, mudstone and carbonate cemented cores: experimental CO_2 SO_2 NO_X O_2 reaction metal mobilisation and fate. International Journal of Coal Geology* 277 104352 104352. https://doi.org/10.1016/j.coal.2023.104352
- Pearce et al., (2025). *Pure CO_2 and impure CO_2-SO_2-NO-O_2 reactions with carbon storage site underlying seals: coaly mudstones and carbonate cemented sandstones. Science of The Total Environment* 963 178391 178391. https://doi.org/10.1016/j.scitotenv.2025.178391

Core examples

Figure 3: QEMSCAN mineral images showing some examples from the lower Precipice Sandstone reservoir, and the upper Precipice Sandstone.

Figure 4: QEMSCAN mineral images showing examples of core samples from the Moolayember Formation (purple regions are siderite cements). These included sandstones, mudstones, siderite filled fractures, coal layers. Total digests also showed elements including Li, Ba, Sr, K, Mg, V, Zn, REE, Fe, Pb, P, and S were relatively elevated in the Moolayember Formation underlying the reservoir.

Methods and results

Experimental setup, ISCO = injection pump, V1-3 = Parr vessels, DA = Data aquisition

Figure 5: Reaction rig. (Pearce, J.K. et al., 2015. SO_2 Impurity Impacts on Experimental and Simulated CO_2-Water-Reservoir Rock Reactions at Carbon Storage Conditions. Chemical Geology, 399,65-86.)

- Core characterisation reservoir and seals including:
- Mineral content
- Metal/element content and sequential extractions
- Porosity and pore throats, permeability
- CO_2-water-rock experimental reactions at reservoir conditions
- Characterisation of water quality and chemistry over time
- Geochemical modelling predictions

Figure 6: Synchroton XFM images and SEM images of metals in minerals in a Moolayember Formation core sample.

Figure 7: SEM image examples of Moolayember Formation samples before and after CO_2-SO_2-NO-O_2 reaction, and left Fe-Cr oxides, clays and mixed carbonates precipitated after reaction.

Figure 8: Change in dissolved ions during CO_2-SO_2-NO-O_2 experimental reactions with different mineralogy cores. These are examples from the Precipice Sandstone. Ca, Fe, Pb, As etc. released to formation water. CO_2 was added at time 0.

- Released element concentrations varied with rock core mineral content (e.g. Figure 8), subset of samples shown
- Precipice Ss – lower pH, dissolved Pb was higher from mudstone (baffle) or minor minerals,
- Dissolved As increased from desorption initially, decreased with precipitation and adsorption
- In upper reservoir or underlying seals: carbonate mineral dissolution, higher pH therefore less silicate mineral dissolution

- From CO_2 experiments, core leaching and core characterisation constructed mineral scripts with metals in specific minerals
- Batch models used to validate reactive surface areas, reacting minerals, mineral metal compositions etc.
- Upscaled subsequently, inclusion of adsorption processes in RTM
- Metals mainly from carbonate mineral dissolution siderite and calcite, with a minor contribution from sulfides and chlorite.
- Mineral precipitation predicted in upper Precipice provides sink for trace metals with additional adsorption.
- With co-injected O_2 precipitation Fe-oxyhydroxides removed metals

Figure 9: Reactive transport model: Predicted concentrations of Pb (ppb) in the plume at the West Moonie 1 injection well site, 3, 10, 50 and 100 yrs after injection.

Conclusions

- ➢ Assessment required multi-pronged approach characterisation, experiments, models.
- ➢ Metals generally hosted in several minerals. Sulphides often contained the highest metal content, but carbonates more easily dissolvedand were the main sources.
- ➢ Precipitation Fe-(hydr)oxides etc. with SO_2-O_2-NO-CO_2 reaction sequestered metals from waters in experiments.
- ➢ Experiments used in predictive and upscaled reactive transport models to assess changes in the reservoir, impacts predicted - restricted to the plume in this case.
- ➢ Predicted ankerite precipitation and adsorption in longer term mineral traps CO_2 and metals -top reservoir/ base cap-rock (consistent with natural analogue observations).
- ➢ Mineral trapping in complex seals not quartz rich reservoir. Outcomes may be different in other reactive reservoirs e.g. basalts, carbonate reservoirs.
- ➢ Methods applicable to other storage areas. Future need for more reservoir appraisals to accelerate carbon storage in a range of reservoir types.

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- Part of this research was undertaken on the XFM beamline at the Australian Synchrotron, Victoria, Australia. This work was supported by the Multi-modal Australian Science Imaging and Visualisation Environment (MASSIVE). We acknowledge travel funding provided by the Synchrotron Access Program (SAP) managed by the Australian Synchrotron and funded by the Australian Government

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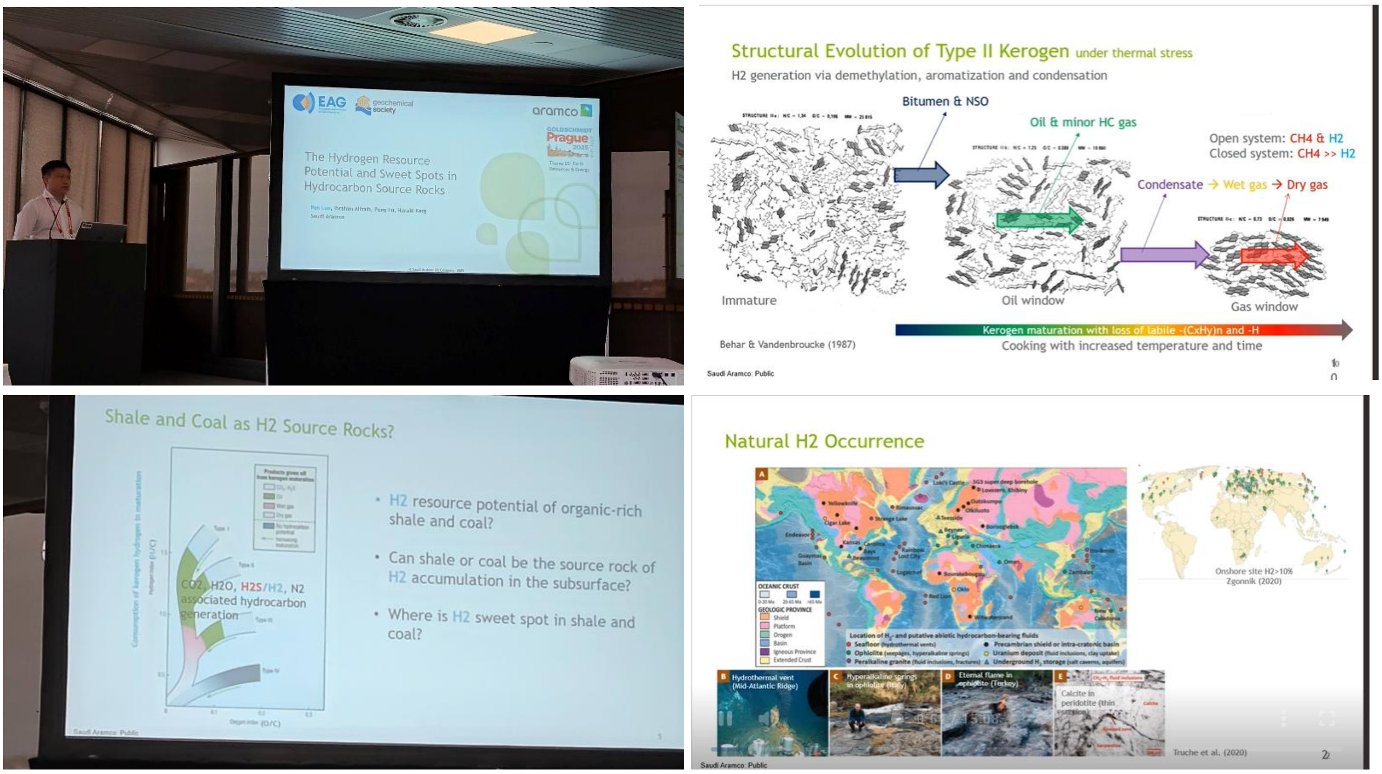
圖 6 封存場址與灌注氣體交互作用研究

2.　地球化學油氣探勘：

除了傳統的油氣資源開發外，頁岩或煤層內的氫能(Hydrogen)和頁岩油氣(Shale oil/gas)，近來也成為非傳統油氣資源的開採對象。傳統油氣資源探勘著重於石油系統的研究，如儲集岩(孔隙與滲透率相當良好的砂岩層)的特性以及阻擋油氣向地表移棲的蓋岩(緻密岩層如頁岩或泥岩)特性，加上地質構造是否有利於油氣移棲與聚積(如背斜構造或地層封閉)。在生油岩的研究上，著重於油氣生成與排放的潛能評估，地層有機物成熟度是否達到油氣生成與排放的門檻，有機物富集程度(總有機碳或 TOC)，有機物的類型是否傾向產油或天然氣等。

非傳統油氣資源，如頁岩油氣、煤層氣等，研究證實生油岩本身也可能有賦存油氣的能力，只是開採技術難度相對於儲集層高。此外，氫能的開發也逐漸被重視(圖7)，在於氫能燃燒後的產物，相較油氣燃燒的產物乾淨。當地層有機物成熟度達到氣窗(gas window)，天然氣可能進一步裂解成氫氣並賦存於生油岩內。


The Hydrogen Resource Potential and Sweet Spots in Hydrocarbon Source Rocks

Structural Evolution of Type II Kerogen under thermal stress

H2 generation via demethylation, aromatization and condensation

Open system: CH4 & H2
Closed system: CH4 >> H2

Behar & Vandenbroucke (1987)

Saudi Aramco: Public

Shale and Coal as H2 Source Rocks?

- H2 resource potential of organic-rich shale and coal?
- Can shale or coal be the source rock of H2 accumulation in the subsurface?
- Where is H2 sweet spot in shale and coal?

Saudi Aramco: Public

Natural H2 Occurrence

Truche et al. (2020)

Saudi Aramco: Public

圖 7 氫能與有機物類型的研究

在介面地球化學(Interfacial Geochemistry)的子議題 (圖 8)，談論微裂隙(孔隙)與流體的交互作用，礦物顆粒間流體的移動性，皆可在相關研究納入參考。在頁岩油移動性的研究，頁岩油於頁岩內的相態(游離態、吸附態、溶解態)，油氣生成產生的超壓現象(Overpressure)。當地層內的頁岩處於不同成熟度下，微裂隙內填充礦物的紋理可顯示對油氣移棲與聚積的影響。這些問題皆可作為地球化學探勘或是油氣移棲模型的討論方向。

Element transport & mineral transformations

Introduction

Overpressure vs. force of overburden

Water's dielectric permittivity in nanoconfinement

Strong dependence of dielectric permittivity on pore size

First-order control on **mineral solubility**, **ion speciation**, and accompanying **transport phenomena** that underly many Earth system applications

Chogani et al. (2025), Nature Geoscience

Research background

- Preliminary research indicates that China's shale oil resource potential is as high as 200.88 billion tons, presenting significant opportunities for exploration and development.
- Shale oil exists in three states: free, adsorbed, and dissolved.

The occurrence of shale oil within the pore space

Distribution of continental shale oil plays in china (Pang.et.al 2023)

Research background

- Oil shale reservoirs primarily consist of microfractures ranging from 50 to 300 nm in diameter, as well as those on a nano to millimeter scale. They provide the main storage space for shale oil.
- The anisotropy and heterogeneous permeability of shale reservoirs affect the flow and migration of shale oil.

Occurrence state of shale oil revised (Xu.et.al 2022)

Different patterns of shale oil migration (Gao.et.al 2024)

Samples

Different textures of cements represent different opening-sealing processes, and their influences on the migration and accumulation of oil and gas are also different.

the Shahejie (Eocene) shales, Bohai Bay Basin

Ro = 0.8% (mature stage)

Fibrous filled fractures

the Wufeng-Longmaxi (Ordovician-Silurian) shales, Sichuan Basin

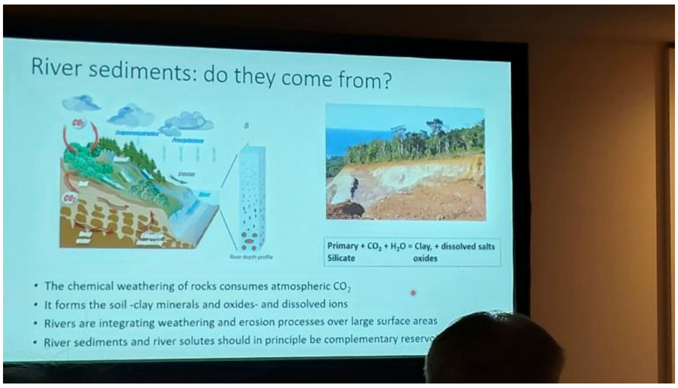
Ro = 2.4% (over-mature stage)

Blocky filled fractures

圖 8 介面地球化學子議題

3. 化學風化及河川沉積作用

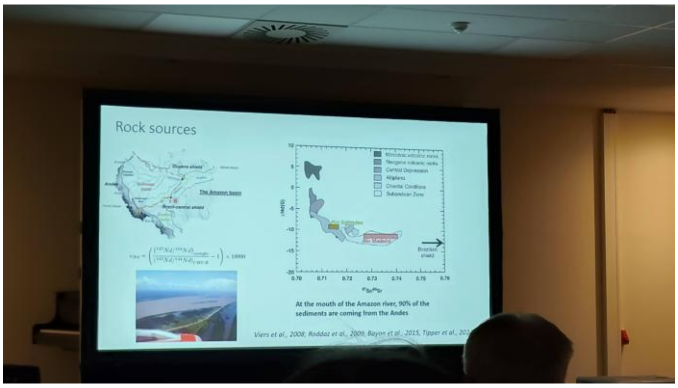
在鑑別沉積物中的碳酸鹽與矽酸鹽風化侵蝕特性，透過總有機碳(TOC)、總無機碳(TIC)、總氮(TN)，碳氮比與碳-13同位素值來實現。此議題可以應用於沉積環境的鑑別，與沉積物來源等相關研究上(圖 9)。



River sediments: do they come from?

Primary Silicate + CO_2 + H_2O = Clay, oxides + dissolved salts

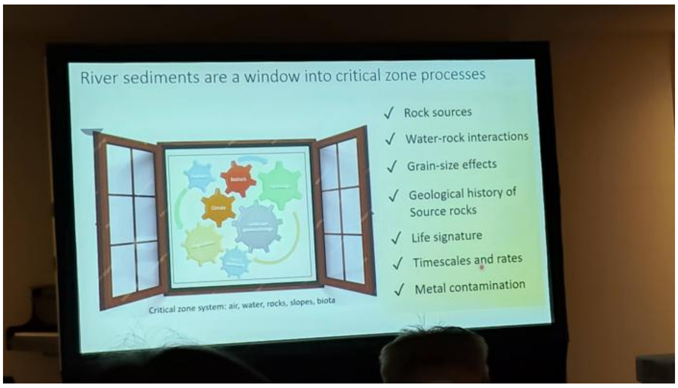
- The chemical weathering of rocks consumes atmospheric CO_2
- It forms the soil -clay minerals and oxides- and dissolved ions
- Rivers are integrating weathering and erosion processes over large surface areas
- River sediments and river solutes should in principle be complementary reservo



Rock sources

At the mouth of the Amazon river, 90% of the sediments are coming from the Andes

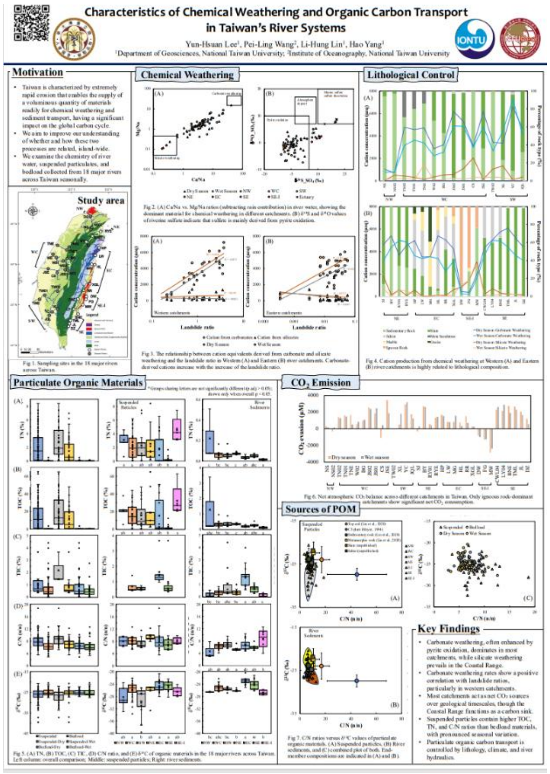
Viers et al., 2008; Roddaz et al., 2009; Bayon et al., 2015, Tipper et al., 202



River sediments are a window into critical zone processes

- ✓ Rock sources
- ✓ Water-rock interactions
- ✓ Grain-size effects
- ✓ Geological history of Source rocks
- ✓ Life signature
- ✓ Timescales and rates
- ✓ Metal contamination

Critical zone system: air, water, rocks, slopes, biota



Characteristics of Chemical Weathering and Organic Carbon Transport in Taiwan's River Systems

Yun-Hsuan Lee[1], Pei-Ling Wang[2], Li-Hung Lin[1], Hao Yang[1]

[1]Department of Geosciences, National Taiwan University; [2]Institute of Oceanography, National Taiwan University

Motivation

- Taiwan is characterized by extremely rapid erosion that enables the supply of a voluminous quantity of materials readily for chemical weathering and sediment transport, having a significant impact on the global carbon cycle.
- We aim to improve our understanding of whether and how these two processes are related, island-wide.
- We examine the chemistry of river water, suspended particulates, and bedload collected from 18 major rivers across Taiwan seasonally.

Study area

Chemical Weathering

Lithological Control

Particulate Organic Materials

CO_2 Emission

Sources of POM

Key Findings

- Carbonate weathering, often enhanced by pyrite oxidation, dominates in most catchments, while silicate weathering prevails in the Coastal Range.
- Carbonate weathering rates show a positive correlation with landslide ratios, particularly in western catchments.
- Most catchments act as net CO_2 sources over geological timescales, though the Coastal Range functions as a carbon sink.
- Suspended particles contain higher TOC, TN, and C/N ratios than bedload materials, with pronounced seasonal variation.
- Particulate organic carbon transport is controlled by lithology, climate, and river hydraulics.

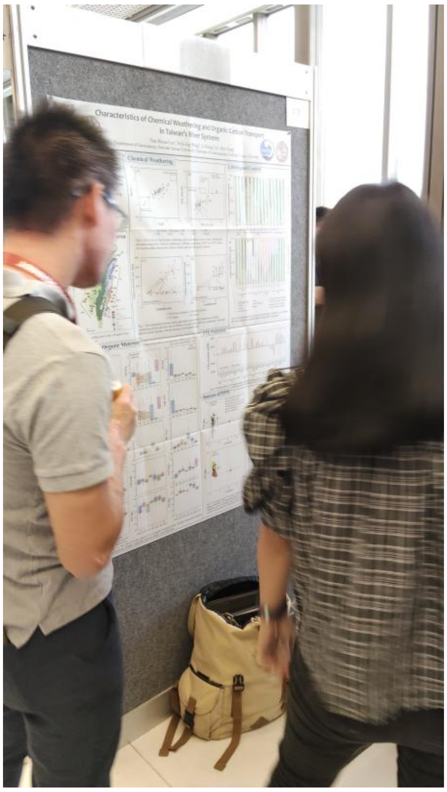
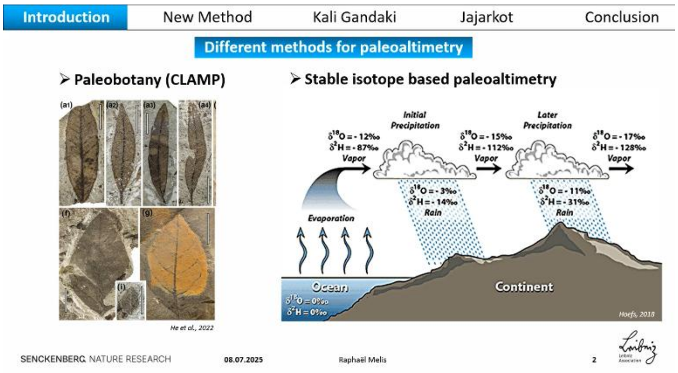


圖 9 化學風化及河川沉積作用議題

化學風化因地表侵蝕作用而加劇，如河川沖刷陸地岩石與土讓，進一步使礦物溶解進入流體，最終進入海洋。這些礦物溶解並釋出陽離子，如鈣(Ca)，鎂(Mg)，鉀(K)，鈉(Na)等，使得海洋鹼度上升，可促使海洋吸收大氣中的二氧化碳，進而達到二氧化碳吸收的效果。

4. 地表作用與氣候衝擊暨陸地及海洋風化訊號及紀錄

在化學風化過程，探討侵蝕速率、侵蝕作用對於陸地碳貯存的釋放有相當影響。岩石內礦物的結晶水可記錄古環境的降水，分析古降水中 δ^{18}O 和 δ^{2}H，以比對古氣候的變化氣候環境；利用稀土元素同位素(Rare Earth Element, REE)進行分析，可追溯水體中營養鹽及有機碳的來源。同位素分析應用於風化與氣候變遷研究，如鋰(Li)、鉛(Pb)、釹(Nd)、鍶(Sr)、鎂(Mg)或是稀土元素等，可做為研究沉積物來源及侵蝕作用的指標(圖 10)。


Introduction | New Method | Kali Gandaki | Jajarkot | Conclusion

Different methods for paleoaltimetry

- Paleobotany (CLAMP)
- Stable isotope based paleoaltimetry

He et al., 2022

Hoefs, 2018

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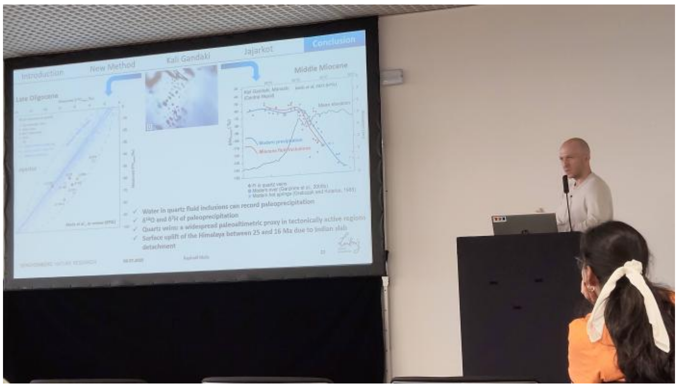
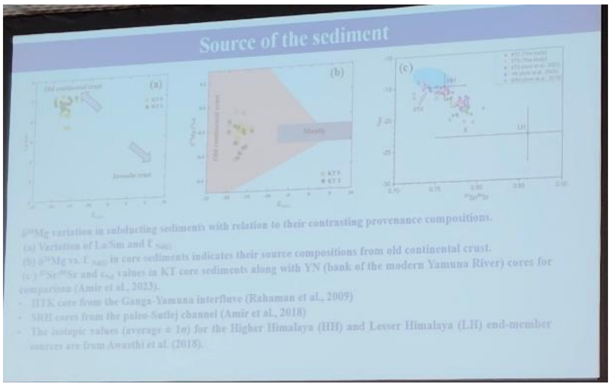
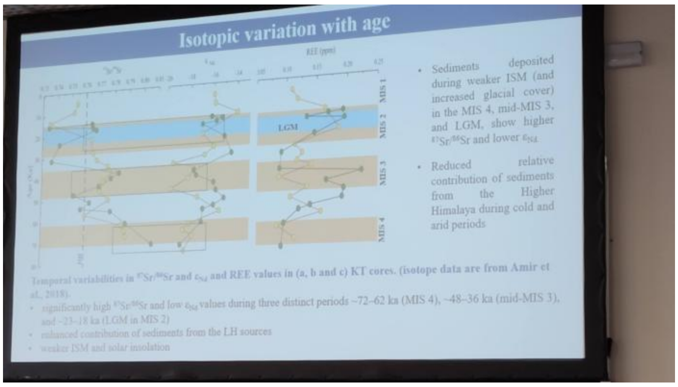


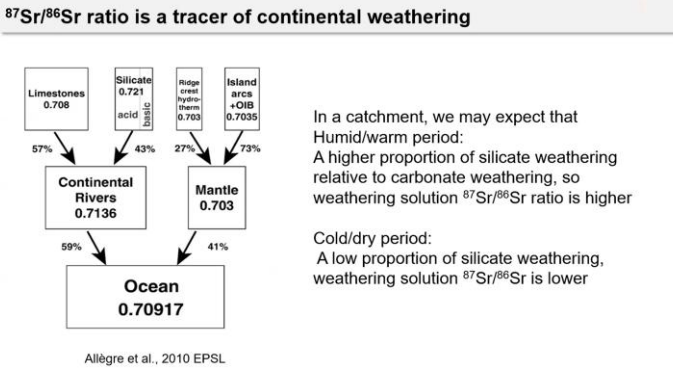

Source of the sediment

δ26Mg variation in subducting sediments with relation to their contrasting provenance compositions.
(a) Variation of La/Sm and ε Nd(t)
(b) δ26Mg vs. ε Nd(t) in core sediments indicates their source compositions from old continental crust.
(c) 87Sr/86Sr and εNd values in KT core sediments along with YN (bank of the modern Yamuna River) cores for comparison (Amir et al., 2023).
- BTK core from the Ganga-Yamuna interfluve (Rahaman et al., 2009)
- SRH cores from the paleo-Sutlej channel (Amir et al., 2018)
- The isotopic values (average ± 1σ) for the Higher Himalaya (HH) and Lesser Himalaya (LH) end-member sources are from Awasthi et al. (2018).


Isotopic variation with age

- Sediments deposited during weaker ISM (and increased glacial cover) in the MIS 4, mid-MIS 3, and LGM, show higher ^{87}Sr/^{86}Sr and lower ε_{Nd}
- Reduced relative contribution of sediments from the Higher Himalaya during cold and arid periods

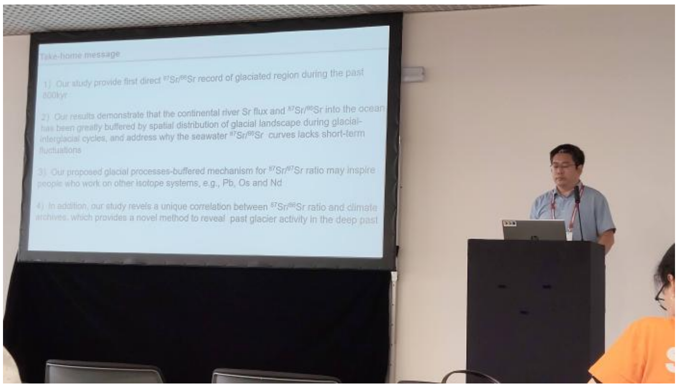
Temporal variabilities in ^{87}Sr/^{86}Sr and ε_{Nd} and REE values in (a, b and c) KT cores. (isotope data are from Amir et al., 2018).
- significantly high ^{87}Sr/^{86}Sr and low ε_{Nd} values during three distinct periods ~72–62 ka (MIS 4), ~48–36 ka (mid-MIS 3), and ~23–18 ka (LGM in MIS 2)
- enhanced contribution of sediments from the LH sources
- weaker ISM and solar insolation


^{87}Sr/^{86}Sr ratio is a tracer of continental weathering

In a catchment, we may expect that
Humid/warm period:
A higher proportion of silicate weathering relative to carbonate weathering, so weathering solution ^{87}Sr/^{86}Sr ratio is higher

Cold/dry period:
A low proportion of silicate weathering, weathering solution ^{87}Sr/^{86}Sr is lower

Allègre et al., 2010 EPSL


Take-home message

1) Our study provide first direct ^{87}Sr/^{86}Sr record of glaciated region during the past 800kyr

2) Our results demonstrate that the continental river Sr flux and ^{87}Sr/^{86}Sr into the ocean has been greatly buffered by spatial distribution of glacial landscape during glacial-interglacial cycles, and address why the seawater ^{87}Sr/^{86}Sr curves lacks short-term fluctuations

3) Our proposed glacial processes-buffered mechanism for ^{87}Sr/^{87}Sr ratio may inspire people who work on other isotope systems, e.g., Pb, Os and Nd

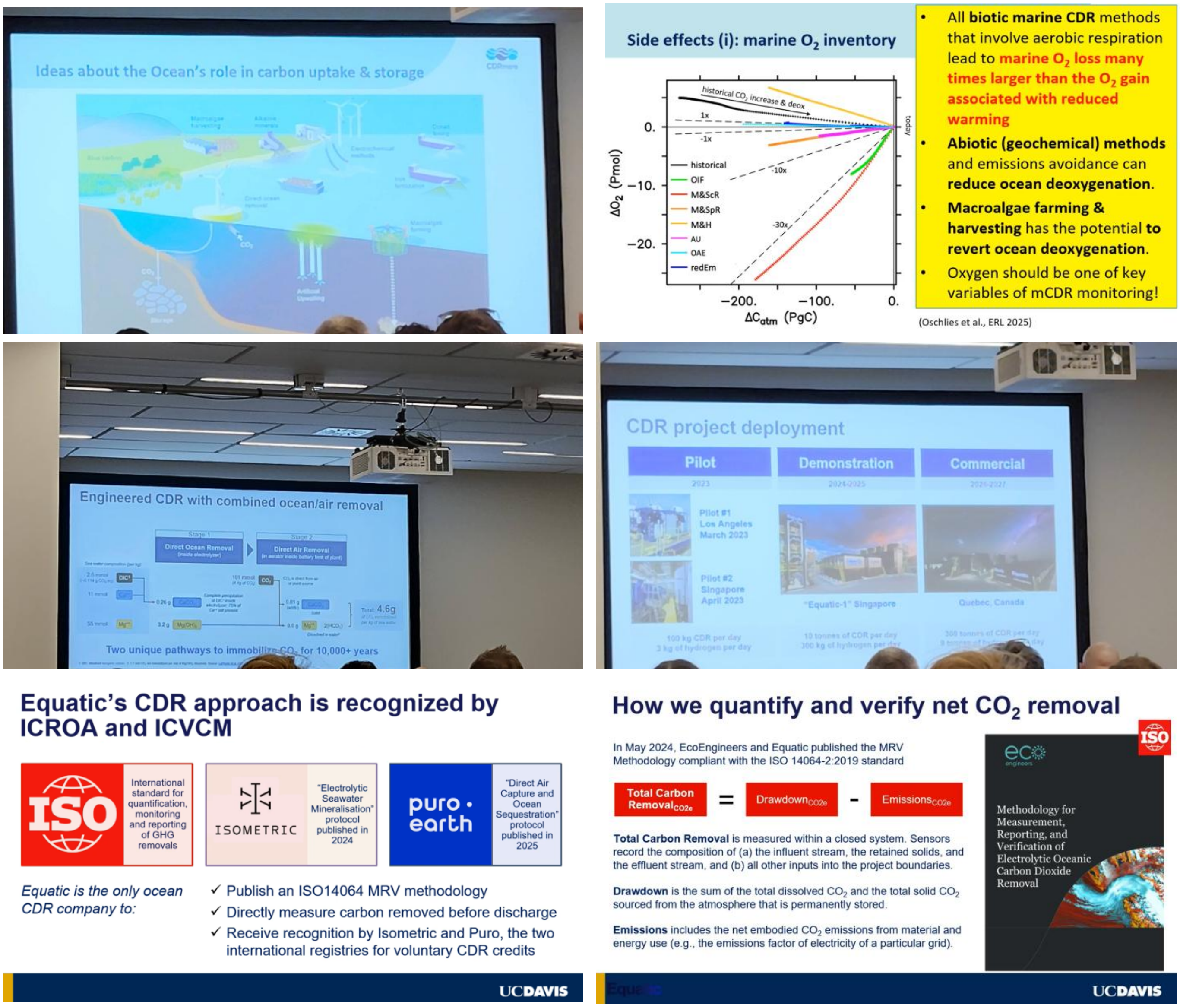
4) In addition, our study revels a unique correlation between ^{87}Sr/^{86}Sr ratio and climate archives, which provides a novel method to reveal past glacier activity in the deep past

圖 10 地表作用與氣候衝擊與陸地及海洋風化訊號議題

5.　二氧化碳移除(Carbon Dioxide Removal, CDR)

由 IPCC(Intergovernmental Panel on Climate Change, 政府間氣候變化專門委員會)定義為從大氣移除與封存二氧化碳的方法(圖 11)，並永久地儲存於地質、陸地或海洋中。子議題多針對海洋鹼度增強(OAE)的研究(圖 12)，認為海洋作為二氧化碳貯存體相當合適，藉由改變海洋的鹼度，以達到海洋吸收二氧化碳的效果。

在國際標準上也有針對 CDR 進行明確規範，可參考 ISO 14064系列。海洋被視為可吸收二氧化碳的介質，議題中介紹了以生物法方式，如海洋鐵肥沃化(Ocean Iron Fertilization, OIF)、海藻養殖法(Macroalgae harvesting)，與海洋鹼度增強(OAE)等方法，試圖利用海洋來吸收大氣中的二氧化碳，但可能造成海洋生態的衝擊，如生物法可能增加耗氧量，使海洋中的氧氣減少造成酸化，故需要加以評估正面與負面影響。



Ideas about the Ocean's role in carbon uptake & storage

Side effects (i): marine O_2 inventory

- All **biotic marine CDR** methods that involve aerobic respiration lead to **marine O_2 loss many times larger than the O_2 gain associated with reduced warming**
- **Abiotic (geochemical) methods** and emissions avoidance can **reduce ocean deoxygenation**.
- **Macroalgae farming & harvesting** has the potential **to revert ocean deoxygenation**.
- Oxygen should be one of key variables of mCDR monitoring!

(Oschlies et al., ERL 2025)

Engineered CDR with combined ocean/air removal

Stage 1
Direct Ocean Removal

Stage 2
Direct Air Removal

Total: 4.6g

Two unique pathways to immobilize CO_2 for 10,000+ years

CDR project deployment

Pilot	Demonstration	Commercial
Pilot #1 Los Angeles March 2023 Pilot #2 Singapore April 2023	"Equatic-1" Singapore	Quebec, Canada
100 kg CDR per day 3 kg of hydrogen per day	10 tonnes of CDR per day 300 kg of hydrogen per day	300 tonnes of CDR per day

Equatic's CDR approach is recognized by ICROA and ICVCM

ISO	ISOMETRIC	puro · earth
International standard for quantification, monitoring and reporting of GHG removals	"Electrolytic Seawater Mineralisation" protocol published in 2024	"Direct Air Capture and Ocean Sequestration" protocol published in 2025

Equatic is the only ocean CDR company to:

✓ Publish an ISO14064 MRV methodology
✓ Directly measure carbon removed before discharge
✓ Receive recognition by Isometric and Puro, the two international registries for voluntary CDR credits

UCDAVIS

How we quantify and verify net CO_2 removal

In May 2024, EcoEngineers and Equatic published the MRV Methodology compliant with the ISO 14064-2:2019 standard

Total Carbon Removal$_{CO2e}$ = Drawdown$_{CO2e}$ - Emissions$_{CO2e}$

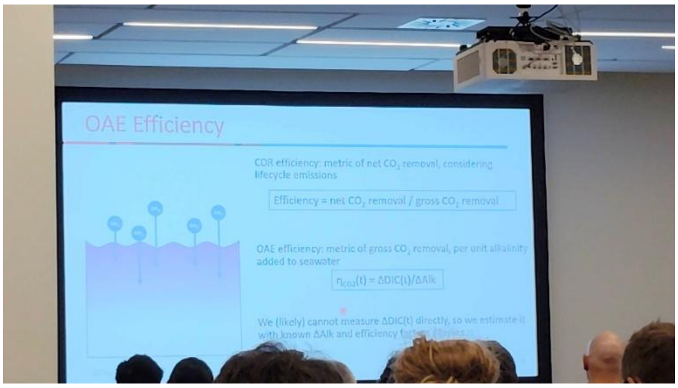
Total Carbon Removal is measured within a closed system. Sensors record the composition of (a) the influent stream, the retained solids, and the effluent stream, and (b) all other inputs into the project boundaries.

Drawdown is the sum of the total dissolved CO_2 and the total solid CO_2 sourced from the atmosphere that is permanently stored.

Emissions includes the net embodied CO_2 emissions from material and energy use (e.g., the emissions factor of electricity of a particular grid).

UCDAVIS

圖 11 二氧化碳移除(CDR)議題



OAE Efficiency

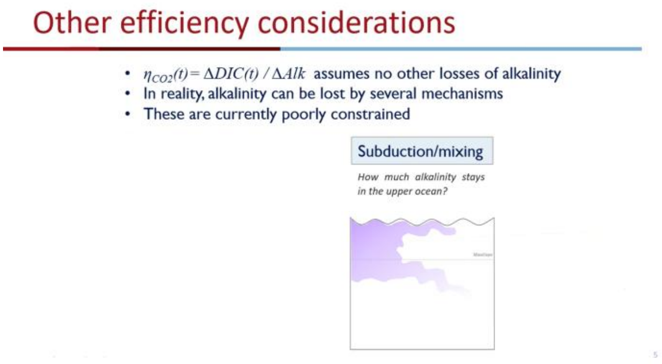
CDR efficiency: metric of net CO_2 removal, considering lifecycle emissions

Efficiency = net CO_2 removal / gross CO_2 removal

OAE efficiency: metric of gross CO_2 removal, per unit alkalinity added to seawater

$\eta_{CO2}(t) = \Delta DIC(t)/\Delta Alk$

We (likely) cannot measure ΔDIC(t) directly, so we estimate it with known ΔAlk and efficiency factors

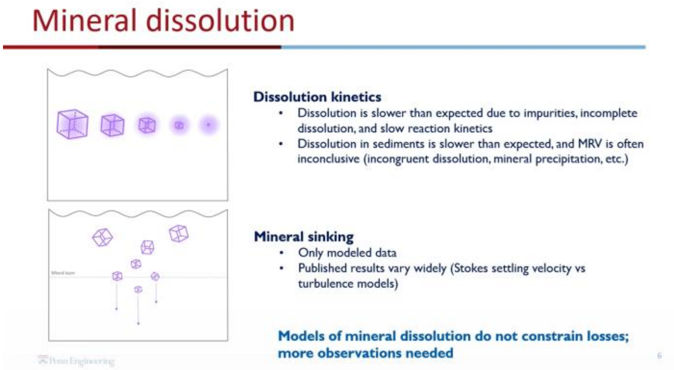


Other efficiency considerations

- $\eta_{CO2}(t) = \Delta DIC(t) / \Delta Alk$ assumes no other losses of alkalinity
- In reality, alkalinity can be lost by several mechanisms
- These are currently poorly constrained

Subduction/mixing

How much alkalinity stays in the upper ocean?



Mineral dissolution

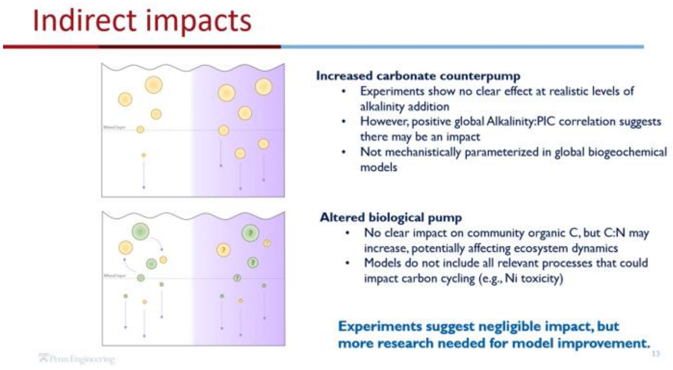
Dissolution kinetics

- Dissolution is slower than expected due to impurities, incomplete dissolution, and slow reaction kinetics
- Dissolution in sediments is slower than expected, and MRV is often inconclusive (incongruent dissolution, mineral precipitation, etc.)

Mineral sinking

- Only modeled data
- Published results vary widely (Stokes settling velocity vs turbulence models)

Models of mineral dissolution do not constrain losses; more observations needed



Indirect impacts

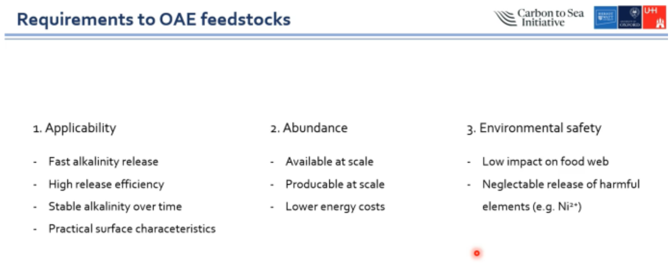
Increased carbonate counterpump

- Experiments show no clear effect at realistic levels of alkalinity addition
- However, positive global Alkalinity:PIC correlation suggests there may be an impact
- Not mechanistically parameterized in global biogeochemical models

Altered biological pump

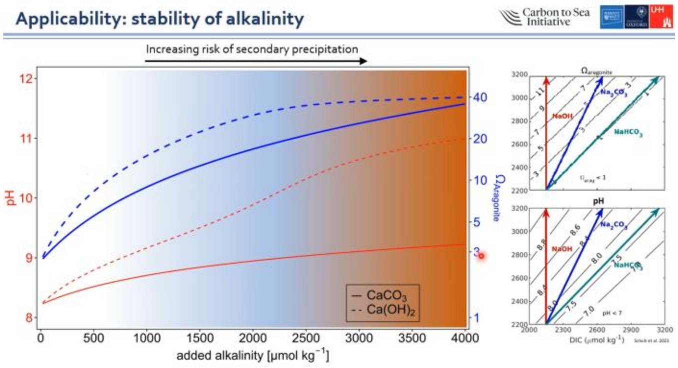
- No clear impact on community organic C, but C:N may increase, potentially affecting ecosystem dynamics
- Models do not include all relevant processes that could impact carbon cycling (e.g., Ni toxicity)

Experiments suggest negligible impact, but more research needed for model improvement.

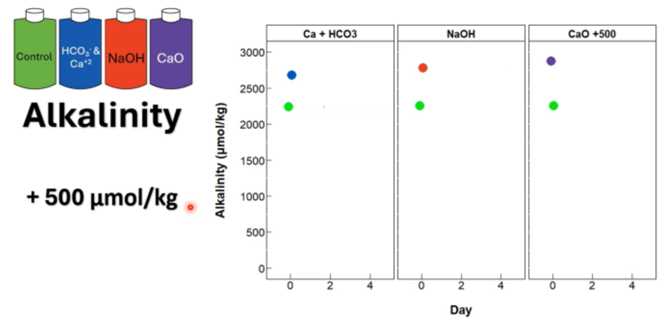


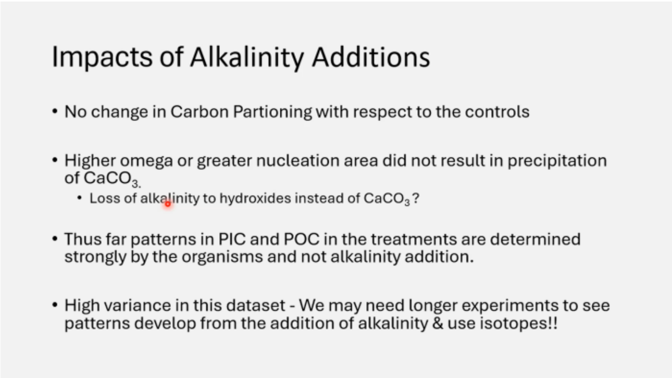
Requirements to OAE feedstocks

1. Applicability
   - Fast alkalinity release
   - High release efficiency
   - Stable alkalinity over time
   - Practical surface characteristics
2. Abundance
   - Available at scale
   - Producable at scale
   - Lower energy costs
3. Environmental safety
   - Low impact on food web
   - Neglectable release of harmful elements (e.g. Ni^{2+})



Applicability: stability of alkalinity





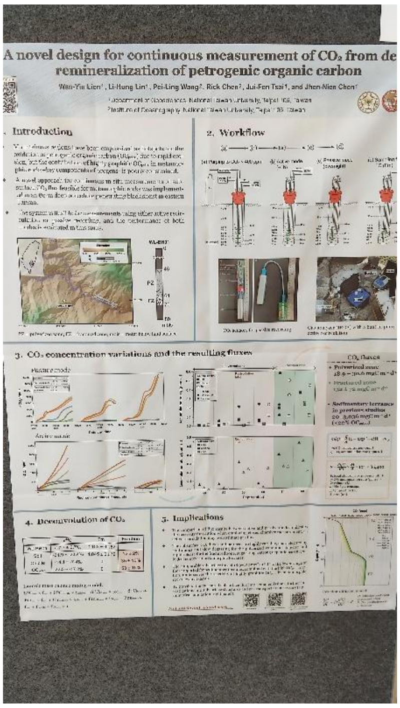
Impacts of Alkalinity Additions

- No change in Carbon Partioning with respect to the controls
- Higher omega or greater nucleation area did not result in precipitation of $CaCO_3$.
  - Loss of alkalinity to hydroxides instead of $CaCO_3$?
- Thus far patterns in PIC and POC in the treatments are determined strongly by the organisms and not alkalinity addition.
- High variance in this dataset - We may need longer experiments to see patterns develop from the addition of alkalinity & use isotopes!!

圖 12 海洋鹼度增強(OAE)議題

6. 壁報論文

壁報論文收集了有關二氧化碳灌注後的監測方法和後續的化學反應研究(圖 13)。二氧化碳在地層內會與周邊的岩石礦物或是游離的油氣產生化學反應，進而產生化學或礦物沉澱，這可能會對鑽井設備造成影響，如阻塞。透過井下分析孔隙的特性，可以了解二氧化碳流體在地層內移動的狀況。灌注二氧化碳的過程對於地層產的應力、孔隙增加、岩體隨壓力灌注增加而膨脹等因素，皆提供日後灌注過程考慮的面向。


A novel design for continuous measurement of CO₂ from de
remineralization of petrogenic organic carbon

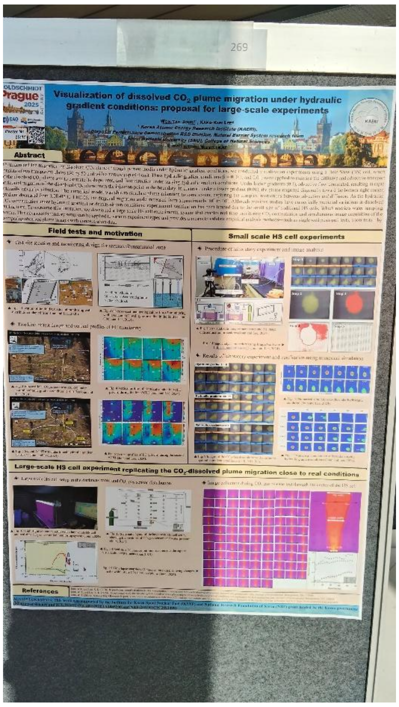
1. Introduction

2. Workflow

3. CO₂ concentration variations and the resulting fluxes

4. Deconvolution of CO₂

5. Implications


269

Visualization of dissolved CO₂ plume migration under hydraulic gradient conditions: proposal for large-scale experiments

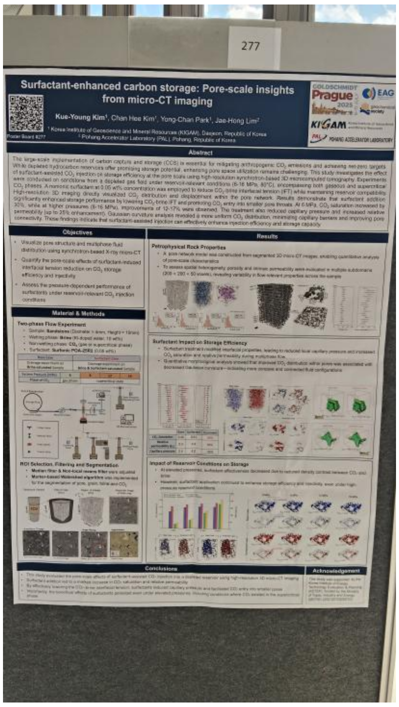
Abstract

Field tests and motivation

Small scale HS cell experiments

Large-scale HS cell experiment replicating the CO₂-dissolved plume migration close to real conditions

References


277

Surfactant-enhanced carbon storage: Pore-scale insights from micro-CT imaging

Kue-Young Kim, Chan Hee Kim, Yong-Chan Park, Jae-Hong Lim

Abstract

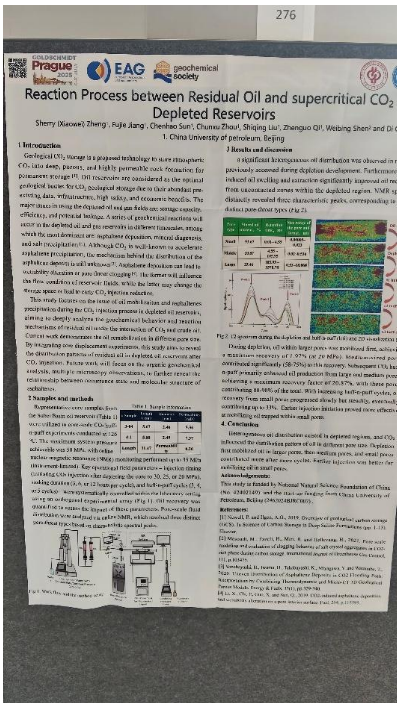
Objectives

Results

Material & Methods

Conclusions

Acknowledgement


276

Reaction Process between Residual Oil and supercritical CO₂ Depleted Reservoirs

Sherry (Xiaowei) Zheng, Fujie Jiang, Chenhao Sun, Chunxu Zhou, Shiqing Liu, Zhenguo Qi, Weibing Shen and Di

1. China University of petroleum, Beijing

1 Introduction

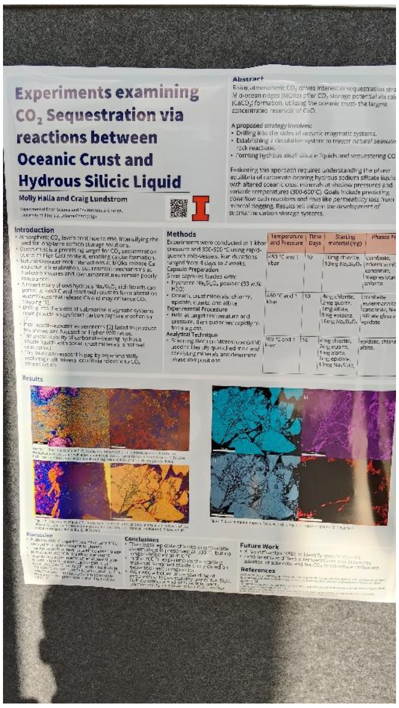
2 Samples and methods

3 Results and discussion

4. Conclusion

Acknowledgement

References


Experiments examining CO₂ Sequestration via reactions between Oceanic Crust and Hydrous Silicic Liquid

Molly Halla and Craig Lundstrom

Abstract

Introduction

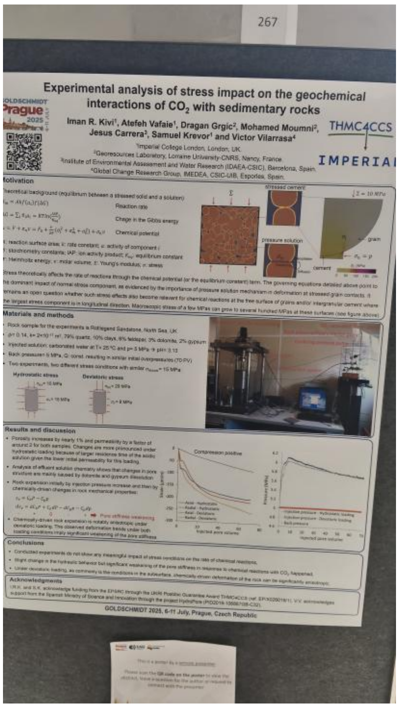
Methods

Results

Conclusions

Future Work

References


267

Experimental analysis of stress impact on the geochemical interactions of CO₂ with sedimentary rocks

Iman R. Kivi, Atefeh Vafaie, Dragan Grgic, Mohamed Moumni, Jesus Carrera, Samuel Krevor, and Victor Vilarrasa

Motivation

Materials and methods

Results and discussion

Conclusions

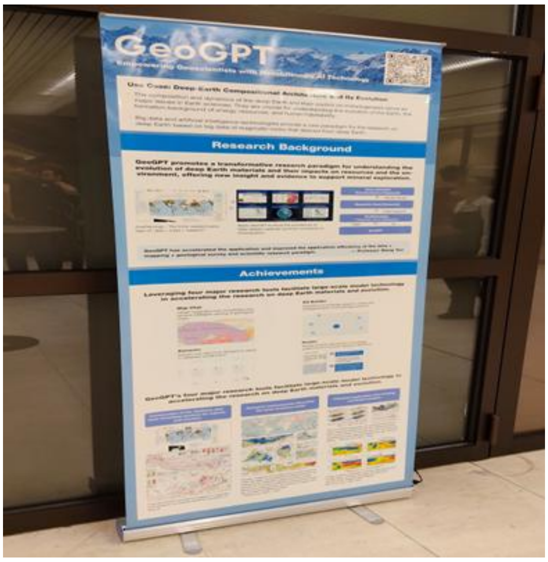
Acknowledgements

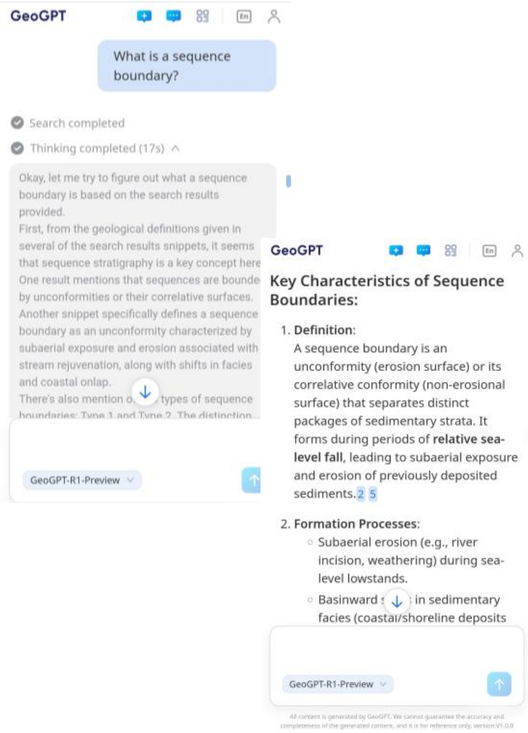
GOLDSCHMIDT 2025, 6-11 July, Prague, Czech Republic

圖 13 CCS 相關壁報論文

7.　GeoGPT 應用

GeoGPT 作為 AI 工具應用(圖 14)，與 ChatGPT 同樣為大型語言模型，透過強化學習訓練以文字互動的方式與使用者交談。相較 ChatGPT，GeoGPT 在使用者詢問地理、地質或地球科學相關的術語會有較準確的描述，對於研究人員而言是一項相當實用的 AI 工具。此外，GeoGPT 也可查閱相關文獻及提供研究建議，在 AI 協助下可以更快速的搜尋，提升研究效率。





What is a sequence boundary?

Search completed

Thinking completed (17s)

Okay, let me try to figure out what a sequence boundary is based on the search results provided.
First, from the geological definitions given in several of the search results snippets, it seems that sequence stratigraphy is a key concept here One result mentions that sequences are bounde by unconformities or their correlative surfaces. Another snippet specifically defines a sequence boundary as an unconformity characterized by subaerial exposure and erosion associated with stream rejuvenation, along with shifts in facies and coastal onlap.
There's also mention o types of sequence

Key Characteristics of Sequence Boundaries:

1. **Definition**:
   A sequence boundary is an unconformity (erosion surface) or its correlative conformity (non-erosional surface) that separates distinct packages of sedimentary strata. It forms during periods of **relative sea-level fall**, leading to subaerial exposure and erosion of previously deposited sediments.2 5
2. **Formation Processes**:
   - Subaerial erosion (e.g., river incision, weathering) during sea-level lowstands.
   - Basinward in sedimentary facies (coastal/shoreline deposits

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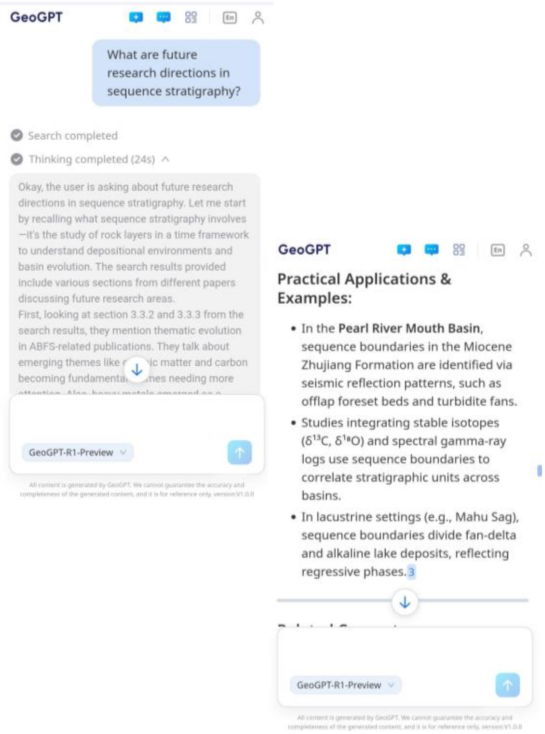

What are future research directions in sequence stratigraphy?

Search completed

Thinking completed (24s)

Okay, the user is asking about future research directions in sequence stratigraphy. Let me start by recalling what sequence stratigraphy involves —it's the study of rock layers in a time framework to understand depositional environments and basin evolution. The search results provided include various sections from different papers discussing future research areas.
First, looking at section 3.3.2 and 3.3.3 from the search results, they mention thematic evolution in ABFS-related publications. They talk about emerging themes like ic matter and carbon becoming fundamenta mes needing more

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Practical Applications & Examples:

- In the **Pearl River Mouth Basin**, sequence boundaries in the Miocene Zhujiang Formation are identified via seismic reflection patterns, such as offlap foreset beds and turbidite fans.
- Studies integrating stable isotopes ($\delta^{13}C$, $\delta^{18}O$) and spectral gamma-ray logs use sequence boundaries to correlate stratigraphic units across basins.
- In lacustrine settings (e.g., Mahu Sag), sequence boundaries divide fan-delta and alkaline lake deposits, reflecting regressive phases.3

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圖 14 GeoGPT 應用(查詢文獻)

三、　心得與建議事項：

地球化學應用於二氧化碳捕捉及封存(CCS)、地球化學油氣探勘、化學風化及河川沉積作用研究，地表作用與氣候衝擊暨陸地及海洋風化訊號及紀錄，以及二氧化碳移除(CDR)等五項主題中，CCS、CDR 和油氣探勘主題與本公司探勘業務及能源轉型息息相關，供未來公司業務發展之參考。

地球化學於 CCS 應用，著重於礦化封存與溶解封存。國外礦化封存的案例以注入二氧化碳水溶液於中生代的玄武岩層或基性(超基性)火成岩，然而台灣本島的地質，其岩性多為沉積岩、變質岩及少數安山岩，案例可能不適用；然而澎湖群島的地質，為中新世火山活動所形成，相對於國外案例的玄武岩層年輕，但論岩性而言，或許是一個機會。在礦化材料方面，投入富含鐵鎂鈣陽離子的礦物，有助於二氧化碳礦化封存。CDR 方法牽涉的層面較廣，以海洋作為二氧化碳的貯存體，透過 OAE 法提升鹼度以利二氧化碳被海水吸收，但也可能有影響海洋生態的疑慮，需要審慎評估。

投入可促進二氧化碳礦化的材料，作為二氧化碳地質封存工程的輔助，加速二氧化碳於地層內礦化效率，尚需要收集國際成功案例與實驗數據進行礦化模擬，以確定是否會產生環境衝擊或地質上的隱憂；基於前述概念，以人工合成方式製作適用於二氧化碳礦化的複合材料之研發，或許是未來研究發展的方向。除了口頭論文發表，也有相關的壁報論文研究，值得研究參考。以上是針對本公司推動 CCS 灌注或監測工程的建議，期望對2025年淨零碳排的目標有助益。

在油氣探勘方面，儘管傳統油氣開發技術相當純熟，但配合政府的減碳政策與潔淨能源的需求提升，未來逐漸降低傳統油氣使用比例。因應能源轉型趨勢，建議將探勘技術延伸至非傳統油氣資源領域，如頁岩油氣與氫能開發，作為本公司業務轉型的重要方向。

最後，在 AI 應用方面，搭配數據來進行預測模型建置，亦是參與本次會議有所啟發。在地球化學實驗及分析過程，會有大量的實驗數據產生，透過 AI 模型進行分析與預測再進行驗證並加以調適，除可以節省時間成本，可能更加熟悉 AI 的運作。因此在未來研究議題上，建議合理的導入 AI 作為輔助工具，並結合實驗分析，以推動技術創新與應用。

四、　具體成效：

參與2025年 Goldschmidt 地球化學會議，藉由相關議題以吸收新的地球化學探勘觀念。除了將探勘觸腳延伸至非傳統油氣資源的研究，如頁岩油氣與氫能，從儲集岩往生油岩探勘，更依循本公司近年的能源轉型策略，結合政府淨零碳排政策，在 CCS 議題上著墨，完成國際 CCS 相關案例資訊收集，如二氧化碳捕捉、地質封存、運輸與監測等工程案例，參考 ISO 文件制定 CCS 相關規範，逐步推動二氧化碳地質封存的試驗計畫。透過本次地球化學會議，得以引入地球化學 CCS 方法與 CDR 概念，如礦化封存及溶解封存，可提升本公司於 CCS 工程的封存效益，在既有鑽井工程的基礎上，導入地球化學方法與環境監測機制，能有效減少大氣中二氧化碳濃度，提升地質封存效率；在環境監測方面，有更多的參考數據來檢視環境影響程度，透過相關的化學量測數值來管控監測作業，以確保二氧化碳灌注過程及封存廠址維護的安全性，降低環境衝擊及危害因素。

在傳統油氣資源探勘方面，本公司致力於國內外礦區的油氣資源評估與開發，已累積許多研究成果。以地球化學分析為例，透過鑽井取得的岩屑或岩心，進行儀器分析獲得實驗數據，進而彙整生油岩資訊並建立地化資料應用系統及資料庫，再結合油氣盆地模擬軟體與 AI 應用工具，進行數據處理及篩選，建構盆地石油系統的模型以預測盆地的生油氣潛能。

非傳統油氣資源探勘，同樣基於地球化學分析的基礎，融合地球物理或地球科學技術，將油氣資源拓展至頁岩油氣或氫能開發領域，此舉不僅降低能源轉型與國際局勢所\帶來的風險，也為本公司未來在探勘領域轉型提供多元選項。

此外，本次地球化學會議除了與本公司地球化學探勘相關的議題，也涵蓋了地球科學、水文、生態、氣候、環境與健康等多面向的議題討論，對於政府於 CCS 制定策略或本公司推動 CCS 工程，具有高度的參考價值，可將其納入考量。未來將持續與社會大眾充分進行溝通及討論，以降低環境衝擊與社會衝突，穩健邁向2050年的淨零碳排目標，以減緩氣候變遷所帶來的影響。