出國報告（出國類別：開會）

出席第 14 屆 CO_2GeoNet 論壇與赴德國亥姆霍茲地科研究中心研討地質探勘技術

服務機關：台灣電力公司綜合研究所
姓名職稱：黃鐘 地質研究專員
派赴國家：義大利、德國
出國期間：108 年 5 月 4 日 至 108 年 5 月 15 日
報告日期：108 年 7 月 10 日

行政院及所屬各機關出國報告提要

出國報告名稱：出席第14屆CO2GeoNet論壇與赴德國亥姆霍茲地科研究中心研討地質探勘技術

頁數 58 含附件：□是■否

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出國類別：□1考察□2進修□3研究□4實習■5其他（開會）

出國期間：108年5月4日至108年5月15日　　出國地區：義大利、德國

報告日期：108年7月10日

分類號/目

關鍵詞：二氧化碳捕獲、地質封存、地熱探勘、地熱發電

內容摘要：(二百至三百字)

二氧化碳捕集與封存為目前全球主要國家降低碳排放之策略之一，本次計畫所參加會議是歐洲碳封存聯盟於義大利威尼斯舉辦之第 14 屆公開論壇，本所人員於該會議中進行本公司碳封存進度之報告，標題為「Carbon Capture and Storage promotion in Taiwan」，使國際各界了解本公司近年來於碳封存相關工作上所進行的努力。

除了碳封存之外，開發低碳甚至零碳發電才是做為發電業減碳工作的治本之道，因此本次出國計畫之中，亦考察了位在德國波茲坦的亥姆霍茲地球科學研究中心，了解該研究中心於地熱探勘、鑽井工程、電廠規劃、以及地熱電廠運維階段地質環境監測之相關技術。本次出國計畫希望藉由交流碳封存與地熱發電之相關知識，作為台灣未來相關發展之借鏡。

本文電子檔已傳至出國報告資訊網（http://open.nat.gov.tw/reportwork）

摘要

工業、石化業與電力業為主要二氧化碳排放來源，且植樹或養藻等生物固碳方法無法在短時間內大量減少以上來源之碳排放量，因此利用二氧化碳捕集與封存(Carbon Capture and Storage, CCS)手段進行二氧化碳之去化與封存即成為全球主要國家降低碳排放之主要策略，故相關之二氧化碳再利用、或是二氧化碳地質封存之組織或聯盟也相繼成立。本次計畫所參加會議是歐洲碳封存聯盟(CO_2GeoNet)於義大利威尼斯舉辦之第 14 屆公開論壇，本所人員於該會議中進行本公司碳封存研究進度之報告，標題為「Carbon Capture and Storage promotion in Taiwan」，使國際各界了解本公司近年來於碳封存相關工作上所進行的努力。

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目錄

第一章　前言

壹、目的

目前大氣層中所含二氧化碳平均濃度已於 2016 年時超過 400 ppm，而近年來，全球學術界亦有多數學者認為，二氧化碳濃度的上升與地球平均氣溫似有正相關的趨勢。因此，為降低地球因溫室效應而造成的氣溫上升現象，降低二氧化碳排放量，同時找出消除二氧化碳的最終處置方法，即成為目前全世界主要國家共同努力的方向。2009 年時於哥本哈根舉行之聯合國氣候變遷大會(COP15)中，提出了哥本哈芬協議，其中建議全球暖化的程度應控制在攝氏兩度之內。而聯合國跨政府氣候變遷研究小組(IPCC)於 2007 年的研究報告中指出，若要將氣溫增加的速率控制在可接受範圍內，全球需於 2020 年時開始降低排碳量。2015 年於巴黎舉行的聯合國氣候變遷大會(COP21)之中，所有締約國一致同意通過巴黎協議，其中特別強調，各國應努力控制全球平均氣溫升幅低於 1.5℃之內。

工業、石化業與電力業為主要二氧化碳排放來源，且植樹或養藻等生物固碳方法無法在短時間內大量減少以上來源之碳排放量，因此利用二氧化碳捕集與封存(Carbon Capture and Storage, CCS)手段進行二氧化碳之去化與封存即成為全球主要國家降低碳排放之主要策略，故相關之二氧化碳再利用、或是二氧化碳地質封存之組織或聯盟也相

繼成立。本次計畫所參加會議是歐洲碳封存聯盟(CO_2GeoNet)於義大利威尼斯舉辦之第 14 屆公開論壇，本所人員於該會議中進行本公司碳封存進度之報告，使國際各界了解本公司近年來於碳封存相關工作上所進行的努力。

除了碳封存之外，開發低碳甚至零碳發電才是做為發電業減碳工作的治本之道，因此本次出國計畫之中，亦考察了位在德國波茲坦的亥姆霍茲地球科學研究中心(GFZ German Research Centre for Geosciences)，了解該研究中心於地熱探勘、鑽井工程、電廠規劃、以及地熱電廠運維階段地質環境監測之相關技術。本次出國計畫希望藉由交流碳封存與地熱發電之相關知識，作為台灣未來相關發展之借鏡。

貳、大型碳封存與捕獲計畫介紹

國際上主要石油公司進行二氧化碳地質封存已有 45 年的歷史(第一個計畫位在美國德州 Val Verde，為提高石油採收率技術地質封存)，目前全球則有 21 個大型(每年灌注量大於 50 萬公噸二氧化碳)二氧化碳地質封存計畫正在營運。這 21 個計畫將可為全球每年封存近 4 千萬噸的二氧化碳，其中主要的地質封存方式為提高石油採收率技術地質封存，而這些計畫之中大部分的二氧化碳來源則與石化產業有關。以下就選出兩個目前正在營運的大型二氧化碳地質封存案例進行介紹，其中包含世界上第一個大型二氧化碳深部鹽水層地質封存計畫、

以及第一個以燃煤發電廠廢氣做為二氧化碳來源的二氧化碳地質封存計畫。

一、 挪威 Sleipner 二氧化碳地質封存計畫

地點：挪威外海，北海中部(57.7159N, 1.87866E)

主要投資與營運單位：挪威國家石油公司(Statoil)

來源：天然氣處理後產物

注入量：約 85 萬噸／年

開始時間：1996 年 9 月

封存方法：外海深部鹽水層地質封存

封存深度：800－1,100 米

計畫簡介：天然氣生產時二氧化碳會伴隨產生，因而降低熱值，所以石油公司在販售天然氣之前要先將二氧化碳移除。由於挪威政府於 1991 年開始徵收碳稅，而挪威國家石油公司為避免繳納鉅額款項，因此自 1996 年開始，該公司即進行世界上第一個二氧化碳深部鹽水層地質封存之計畫。此計畫雖在外海進行，但仍然施以足夠的地球物理探測以監測二氧化碳團塊的移棲模式，包含以一次三維震測調查之成果做為背景值，另外再施測八次震測調查測量觀察二氧化碳團塊移棲之速率。同時在海床上亦架設四台微重力儀進

行監測，也曾經施測過一次大地電磁測量。

二、 加拿大 Boundary Dam 燃煤電廠二氧化碳捕獲計畫

地點：加拿大薩克其萬省（49.0974N, 103.031W）

主要投資與營運單位：加拿大薩克其萬電力公司（SaskPower）

來源：燃煤發電廠煙氣

注入量：約 100 萬噸／年

開始時間：2014 年 10 月

封存方法：陸上提高石油採收率技術地質封存

封存深度：約 1,500 米

計畫簡介：本計畫的二氧化碳來源是 Boundary Dam 發電廠三號機組的煙氣，此計畫是世界上第一個整合商轉燃煤發電廠的大型二氧化碳地質封存計畫。該計畫不僅僅是二氧化碳捕集與地質封存計畫，亦同時為老舊燃煤機組更新為二氧化碳捕集相容規格改善計畫。此三號機組於 1969 年所興建，裝置容量為 139MW，原本的預定除役年為 2013 年。在 2008 年初時，薩克其萬省與薩克其萬電力公司決定將此機組改建，升級為可以進行二氧化碳捕集之機組。此升級計畫主要包括鍋爐改建與汽機更換等，由於更新後的機組需支援二氧化碳捕集廠，所以部分能量會挪用至捕集製程

之中，因此新機組的裝置容量為 110MW，約為原機組之 80%。該機組於 2010 年 12 月取得運轉許可，二氧化碳捕集廠之運轉許可則於 2011 年 4 月取得。

參、行程說明

本次出國行程為 108 年 5 月 4 日至 5 月 15 日共計 12 天，出國行程表如下：

日　期	工　作　內　容
5/4-5/5	往程 (台北－德國法蘭克福－義大利威尼斯)
5/6-5/9	參加 CO_2GeoNet 第 14 屆公開論壇
5/10	移動日 (威尼斯－德國斯圖加特－柏林－波茲坦)
5/11-5/13	考察亥姆霍茲地球科學研究中心 (GFZ)
5/14-5/15	返程 (波茲坦－柏林－荷蘭阿姆斯特丹－台北)

參與公開論壇成員，由左至右為台灣綜合研究院左峻德所長、清華大學談駿嵩教授、台灣大學馬小康教授、本公司綜研所黃鐘研究專員。

第二章　考察過程與紀實

壹、CO_2GeoNet 第 14 屆公開論壇

108 年 5 月 6 日歐洲二氧化碳地質封存協會 CO_2GeoNet 在義大利威尼斯 San Servolo 島舉行第 14 屆公開論壇，其主軸為「Act now for zero emissions」，議程及重點說明如下：

一、 論壇議程

Overall schedule

	Monday, 6 May	Tuesday, 7 May	Wednesday, 8 May	Thus, 9 May
Morning	CSLF - CO2GeoNet workshop CO_2 storage stories: learning by doing	Open Forum • *Keynote Talk* – Setting the scene • Four years after the Paris agreement	Open Forum • Communication – putting people at the centre • Breakout sessions	CO2GeoNet – ENOS workshop National networking: driving CCS forward
Afternoon	CSLF - CO2GeoNet workshop CO_2 storage stories: learning by doing	Open Forum • Plug & Play Storage – how close are we? • Leading edge trends in CCUS	Open Forum • Integrating CCS	CLIMIT - ARI workshop Towards commercialization: insights from US and Norway
Evening	Ice breaker	Gala dinner		

本次會議分為四天進行，第一天為各國二氧化碳地質封存之技術經驗分享，第二天為二氧化碳地質封存之發展現況，第三天為陸域二氧化碳地質封存之民眾溝通討論，以及整合二氧化碳地質封存與其他二氧化碳再利用或綠能之相關議題，最後一天為各國二氧化碳地質封存之進度簡介，以及美國與挪威的二氧化碳地質封存商轉計畫之現狀。本報告內關於此公開論壇之詳細議程及重點說明均來自該會議網站：http://conference2019.co2geonet.com/。

Monday May 6 - Pre-Open Forum workshop

CO_2 storage stories: learning by doing
organized by *CSLF and CO_2GeoNet*

11:00 Welcome and aims of workshop
Mark Ackiewicz, CSLF and US Department of Energy, US

Session 1: Seismicity
Chair: Kyle Worth, Worthy Environmental Engineering

11:10 Decatur lessons learned
Randall Locke, Illinois State Geological Survey, US

11:30 Recent results of Tomakomai CCS demonstration project
Yoshihiro Sawada, JCCS, Japan

11:50 Discussion

12:20 Lunch break

Session 2: Injectivity
Chair: John Scowcroft, GCCSI

13:30 ENOS project: injectivity changes produced by the alternate injection of CO_2 and brine
Carlos de Dios, CIUDEN, Spain

13:50 Industrial scale CO_2 injection: geology vs. business
John Midgley, British Geological Survey, UK

14:10 Carbon storage and the living subsurface: how CO_2 and CO_2/H_2S injections can prompt microbial communities to evolve and bloom
Rachael Moore, Institut de Physique du Globe de Paris, France

14:30 Discussion

15:00 Coffee break

Session 3: Monitoring
Chair: Didier Bonijoly, BRGM

15:30 Injection, measurement, monitoring and verification at Aquistore: lessons learned by doing
Erik Nickel, Petroleum Technology Research Center, Canada

15:50 Optimizing monitoring to document storage permanence: lessons learned at SECARB "early" test at Cranfield
Susan Hovorka, Gulf Coast Carbon Center, University of Texas, US

16:10 The convergence of modelling and monitoring: reviewing conformance at Sleipner using geophysical data
Jim White, British Geological Survey, UK

16:30 Discussion

17:00 Workshop close

Monday May 6 - Icebreaker welcome

Ton Wildenborg, Former President of CO_2GeoNet

Tuesday May 7 - Open Forum - Day 1

8:30 Registration

9:15 Welcome
Sergio Persoglia, CO_2GeoNet Secretary General

9:20 Objectives of the 14th CO_2GeoNet Open Forum
Ceri Vincent, CO_2GeoNet President

Keynote Talk – Setting the scene

09:30 CO_2 Storage - time to shift gear
Chris Davies, former European Parliament CCS rapporteur

10:00 Discussion

10:15 Coffee break

Session 1: Four years after the Paris agreement
Update on trends and achievements towards climate goals

Chair: Ceri Vincent, CO_2GeoNet-BGS & Chris Davies, former European Parliament CCS rapporteur

10:45 CCUS in the Clean Energy Transition - EU perspective
Vassilios Kougionas, European Commission - DG Research and Innovation, Belgium

11:05 Tackling industrial emissions in The Netherlands: the role of CCS
Joëlle Rekers, Ministry of Economic Affairs and Climate, The Netherlands

11:25 Carbon utilization challenges and opportunities
Mark Ackiewicz, Department of Energy, US

11:45 The status and challenges of CCS in South Korea
Seong-Taek Yun, Korea CO_2 storage environmental management - KCOSEM, Korea

12:05 Discussion

12:30 Lunch break

Session 2: Leading edge trends in CCUS
Utilisation & storage for long-term emission reduction and removal of CO_2
Chair: Roman Berenblyum, CO_2GeoNet-NORCE & Jonas Helseth, Bellona

13:45 **Green hydrogen – transitioning our gas supplies**
Lars Ingolf Eide, Research Council of Norway

14:05 **CCUS in the cement industry: CLEANKER technology, progress and project perspectives**
Martina Fantini, Laboratory of Energy and Environment Piacenza, Italy

14:25 **CCU value chains in Norway**
Catherine Boccadoro, CO_2GeoNet-NORCE, Norway

14:45 Discussion

Session 3: Plug & Play Storage – how close are we?
Providing a transport and storage service
Chair: Isabelle Czernichowsi-Lauriol, CO_2GeoNet-BREM & John Scowcroft, GCCSI

15:00 **The public good case for European CO_2 transport & storage networks**
Jonas Helseth, Bellona, Norway

15:20 **Building a European CO_2 transport network - Porthos project**
Bram Herfkens, EBN - Port of Rotterdam, The Netherlands

15:40 Coffee break

16:10 **CO_2: an emerging business line**
Laurent Fritz, Total E&P Norge as, Norway

16:30 **The road ahead: building on successful CCS project experience**
Diego Alejandro Vasquez Anzola, Norske Shell AS, Norway

16:50 **Advancements in establishing business case scenarios for fully integrated projects**
Charles Gorecki, Energy & Environmental Research Center, US

17:10 Discussion

17:25 **Closing remarks Day 1**
Roman Berenblyum, CO_2GeoNet ExCo Chair

18:15 Departure by boat to the Gala Dinner

Wednesday May 8 - Open Forum - Day 2

8:50 **Welcome and introduction**
Sergio Persoglia, CO_2GeoNet Secretary General

Session 4: Communication – putting people at the centre
Engaging with, and creating benefits for the community
Chair: Sabina Bigi, CO_2GeoNet-Sapienza University & Susan Hovorka, Gulf Coast Carbon Center

08:55 **Communicating CCS**
John Scowcroft, GCCSI, Belgium

09:15 **Onshore storage: the solution on your doorstep - ENOS project**
Marie Gastine, CO_2GeoNet-BRGM, France

09:35 **Engaging with the local community - ENOS case studies and materials**
Samuela Vercelli, CO_2GeoNet-Sapienza University, Italy & Mathew Humphrey, University of Nottingham, UK

09:55 **New business models and new employment opportunities**
Anne-Beth Skrede, Norwegian Confederation of Trade Unions, Norway

10:15 **Discussion**

10:35 *Coffee break*

Session 4: Continued
The role of CCS in the energy transition (breakout sessions)
Building on the knowledge shared during previous sessions, participants will work together to prepare key messages we can share with the public and other stakeholders, to illustrate how CO_2 storage can contribute to the energy transition and to achieving the climate targets (topics to include contexts for application of CO_2 storage, possible synergies with renewables and other technologies, relationship with energy storage, etc.).
Chair: Samuela Vercelli, CO_2GeoNet-Sapienza University

11:00 **Introduction**
Samuela Vercelli, CO_2GeoNet-Sapienza University, Italy

11:15 **Breakout sessions**

12:15 **Feedback from breakout sessions & discussion**

12:45 *Lunch break*

Session 5: Integrating CCS
Fitting CCS into our low carbon society
Chair: Ton Wildenborg, CO_2 GeoNet-TNO & Kyle Worth, Worthy Environmental Engineering

14:00 **Legal and regulatory issues: technical ISO standards as an important piece to commercialize CCUS**
Ingvild Ombudstvedt, IOM Law, Norway

14:20 **How much storage is really needed and when? Preliminary results from UK CO_2 storage projects**
Jonathan Pearce, CO_2GeoNet-BGS, UK

14:40 **Geological CO_2 buffering for re-use - ENOS project**
Mariëlle Koenen, CO_2GeoNet-TNO, The Netherlands

15:00 **Discussion**

15:20 *Coffee break*

Session 5: Continued
Chair: Niels Poulsen, CO_2GeoNet-GEUS & Didier Bonijoly, Club CO_2 France

15:50 **CCS demonstration projects of Japan - Tomakomai and other projects**
Yoshihiro Sawada, JCCS, Japan

16:10 **Challenges to injection start-up in a gas field due to thermal issues**
Filip Neele, CO_2GeoNet-TNO, The Netherlands

16:30 **Scaling up CCS testing and deployment in the Illinois Basin**
Randall Locke, Illinois State Geological Survey, US

16:50 **Discussion**

17:10 **Closing remarks Day 2**
Ton Wildenborg, Former President of CO_2GeoNet

Thursday May 9 - Post-Open Forum workshop

National networking: driving CCS forward

organized by *CO_2GeoNet and ENOS project*

Chair: Ceri Vincent, BGS & Vit Hladik, Czech Geological Survey

09:00 Aims of workshop
Ceri Vincent, BGS, UK

09:15 Storage Forum
Eva Halland, Norwegian Petroleum Directorate, Norway

09:25 Club CO_2
Didier Bonijoly, Club CO_2 President and BRGM, France

09:35 CO_2 Club Romania
Andreea Burlacu, CO_2 Club and GeoEcoMar, Romania

09:45 Supporting CCS roll-out in the UK - Carbon Capture and Storage Association
Ceri Vincent, BGS, UK

09:55 CATO and CCS in the Netherlands
Jan Hopman, TNO, The Netherlands

10:05 PTECO: a vision on the present and the future of CCS in Spain
Paula Cantelli, IGME, Spain

10:15 CO_2 Club
Sergio Persoglia, OGS, Italy

10:25 Coffee break

10:55 Midwest Geological Sequestration Consortium - partnership experiences
Randall Locke, Illinois State Geological Survey, US

11:05 Public outreach activities of Tomakomai CCS demonstration project
Yoshihiro Sawada, JCCS, Japan

11:15 Carbon Capture and Storage promotion in Taiwan
Chung Huang, TCCSUA and Taiwan Power company, Taiwan

11:25 Large scale zero-to-negative industrial emissions now a reality
Michael Monea, International CCS Knowledge Center, Canada

11:35 Discussion - role for national actors in driving CCS forward

12:30 Lunch

Thursday May 9 - Post-Open Forum workshop

Towards commercialization: insights from US and Norway

organized by *CLIMIT (Norway) and ARI (US)*

Chair: Roman Berenblyum, NORCE & Kris Piessens, Geological Survey of Belgium

13:30 Aims of workshop and introduction
Roman Berenblyum, NORCE, Norway

13:40 Financial aspects of storage in saline aquifers
David Riestenberg, ARI, US

14:00 EOR clusters and business cases
George Koperna, ARI, US

14:20 Regulatory and financial aspects of 45Q
Michael Godec, ARI, US

14:40 Coffee break

15:00 Storage evaluation and risk assessment from idea to realization - from demo to field scale
Mark Carpenter, Gassnova, Norway & Diego Alejandro Vazquez Anzola, Shell, Northern Lights project, Norway

15:20 CO_2 storage license - Norwegian Petroleum Directorate perspective
Eva Halland, Norwegian Petroleum Directorate, Norway

Business case - from Sleipner and Snøhvit to Northern Lights
Szczepan Piotr Polak, Equinor, Northern Lights project, Norway

15:40 Streamlining industrial CCS - future upsides
Laurent Fritz, Total, Northern Lights project, Norway

Aurora project risk
Renata Meneguolo, Equinor, Northern Lights project, Norway

16:00 Joint debate and Q&A session

16:50 Summary: key messages from actual experience on what it takes to get industrial CCS going
Roman Berenblyum, NORCE, Norway

17:00 Workshop ends

二、 論壇重點

CO_2GeoNet 共有來自全球 21 個國家的 30 個會員，而第 14 屆公開論壇則有來自 24 個國家的 96 位專家參與。這 24 個國家分別為歐洲的比利時、克羅埃西亞、捷克、丹麥、愛沙尼亞、法國、德國、愛爾蘭、義大利、荷蘭、挪威、波蘭、羅馬尼亞、塞爾維亞、斯洛伐尼亞、西班牙、瑞典、土耳其、英國；美洲的加拿大、美國；亞洲的日本、韓國、以及台灣。

本次論壇中有數個討論二氧化碳地質封存與地震之關聯性的報告，亦有討論地下監測技術之報告，基於本公司目前面臨二氧化碳地質封存之關鍵議題均為地質封存之安全性，因此本章節以地質封存安全性之相關議題為主進行重點節錄。

(1) Lessons Learned from Decatur, Illinois, USA. Randy Locke, Illinois State Geological Survey, US.

本報告為伊利諾地質調查所發表，主要說明伊利諾州 Decatur 計畫分為兩階段，第一期將於 2020 年結束，總共灌注 100 萬噸的二氧化碳作為先導試驗之用。由於該計畫是伊利諾州第一個大型先導灌注計畫，因此進行了嚴謹的地質調查，同時也在 2015 年通過了伊利諾州的 VI 級認證。該計畫第二期於 2017 年 4 月展開，截至 2019 年 4 月已灌入 119 萬 5300 噸之二氧化碳，目標為注入 500 萬噸二氧化碳(圖 1)。

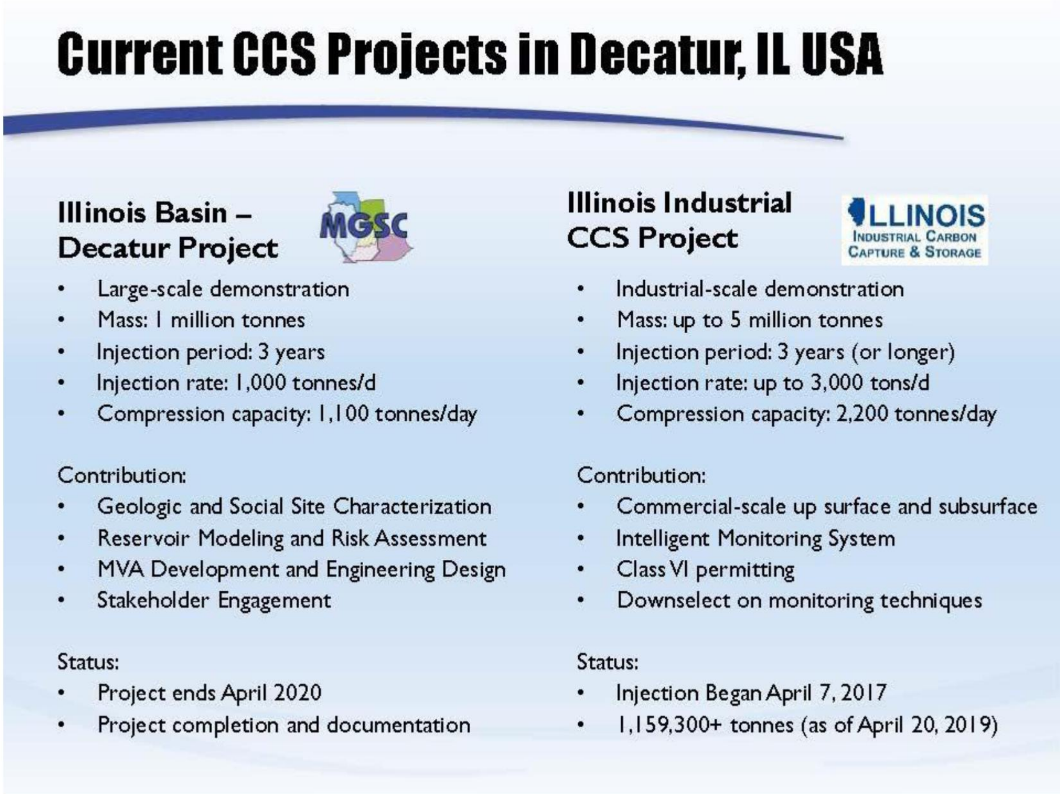


圖 1 伊利諾州 Decatur 計畫概述

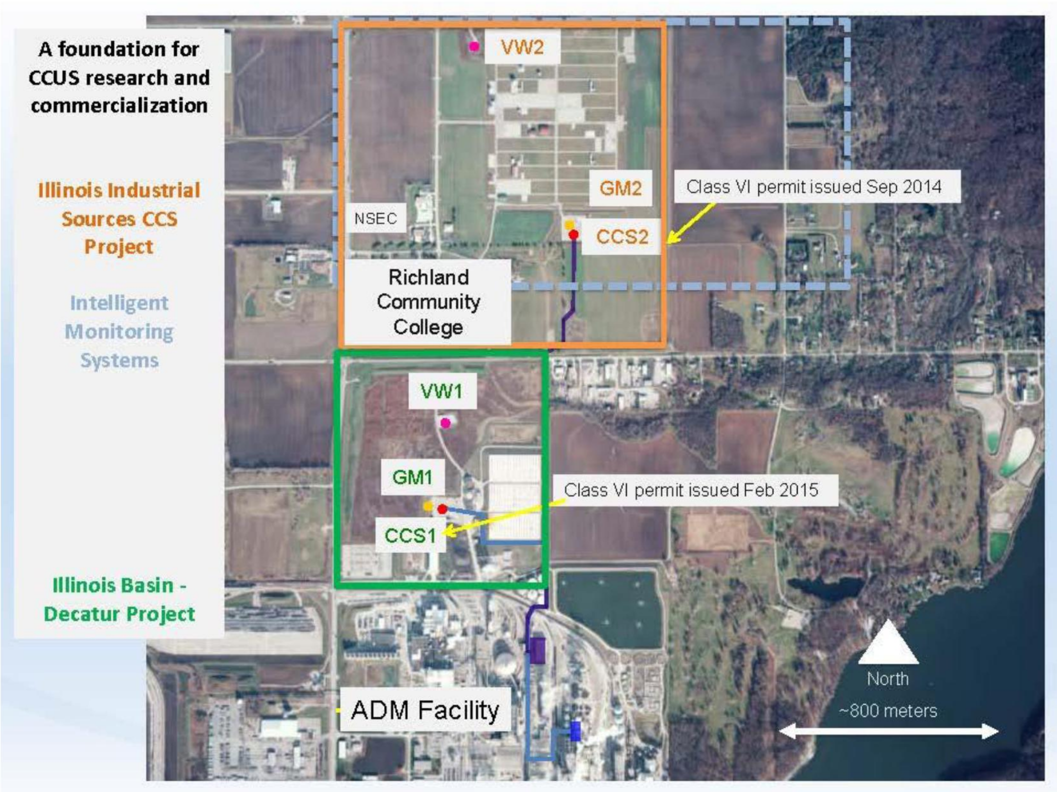


圖 2 伊利諾州 Decatur 計畫平面圖

該計畫之第一期與第二期各有一口灌注井與兩口監測井，兩個灌注井場都位於二氧化碳來源之北側。第一期灌注場緊鄰提供二氧化碳之工廠，第二期則位於第一期之北側(圖 2)。

第一期灌注之灌注深度接近 6,000 英呎，約 1,800 公尺深，兩口監測井分別監測溫度與壓力(VW1)，以及進行震波探勘(GM1)，三口井之地下立體分布狀況詳如圖 3。

該區於灌注前即開始進行地震監測，而經過 1.5 年之資料蒐集，發現灌注區域內並非地震活躍區，僅有 8 起規模小於 0 之無感地震，且其中 2 起地震之深度還遠深於儲集層位置，代表本區之地震對二氧化碳灌注無法造成影響(圖 4)。

自第二期灌注開始後，地震監測結果發現多數無感地震均發生於儲集層之下，但因為二氧化碳灌注後會向上遷徙，所以無感地震可能與灌注工程無直接關聯(圖 5)。

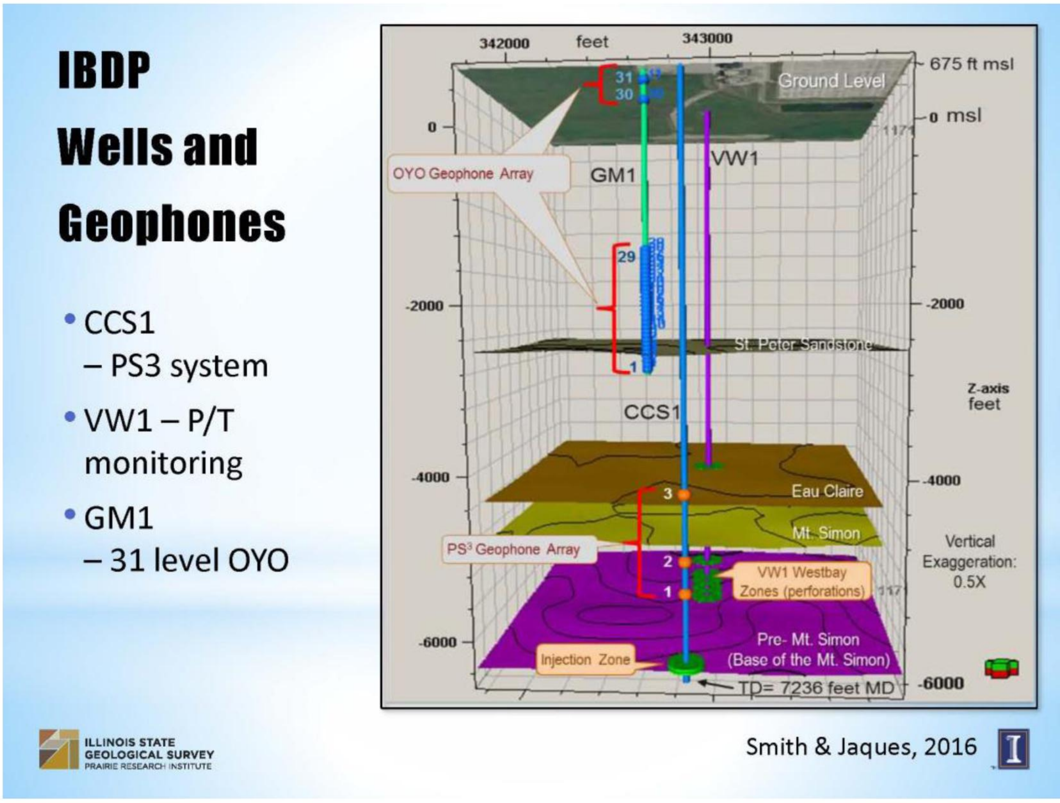


圖 3 Decatur 計畫第一期井下模型

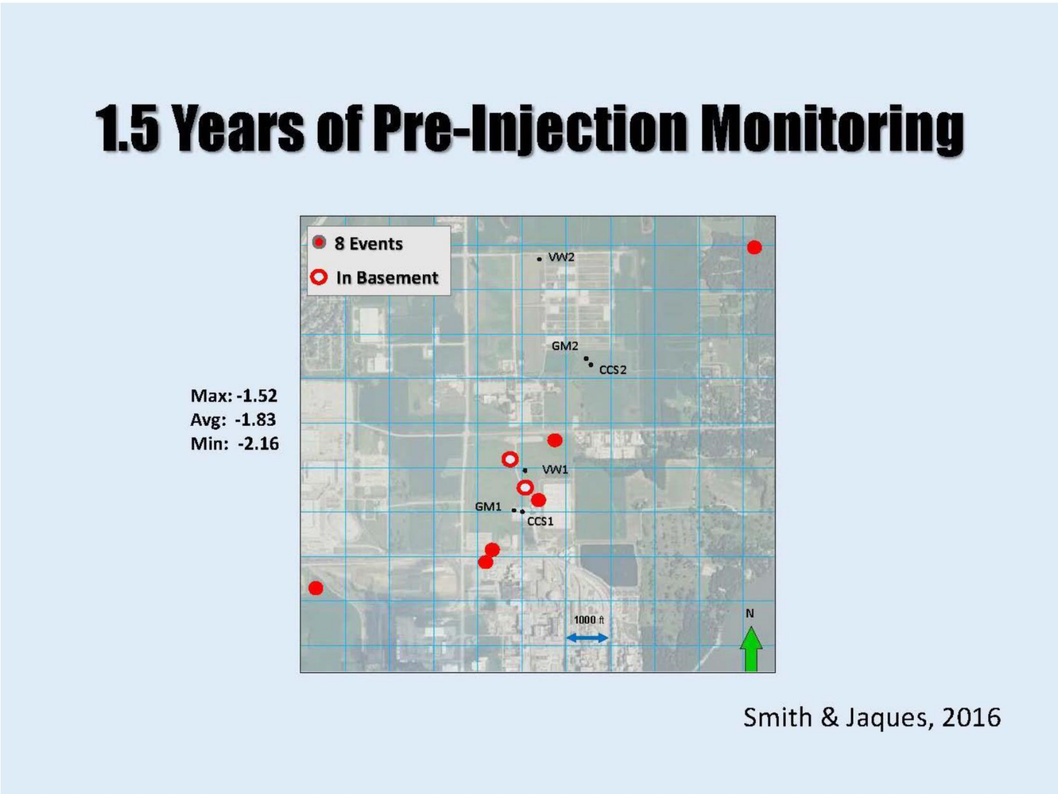


圖 4 Decatur 計畫灌注前 1.5 年地震監測成果

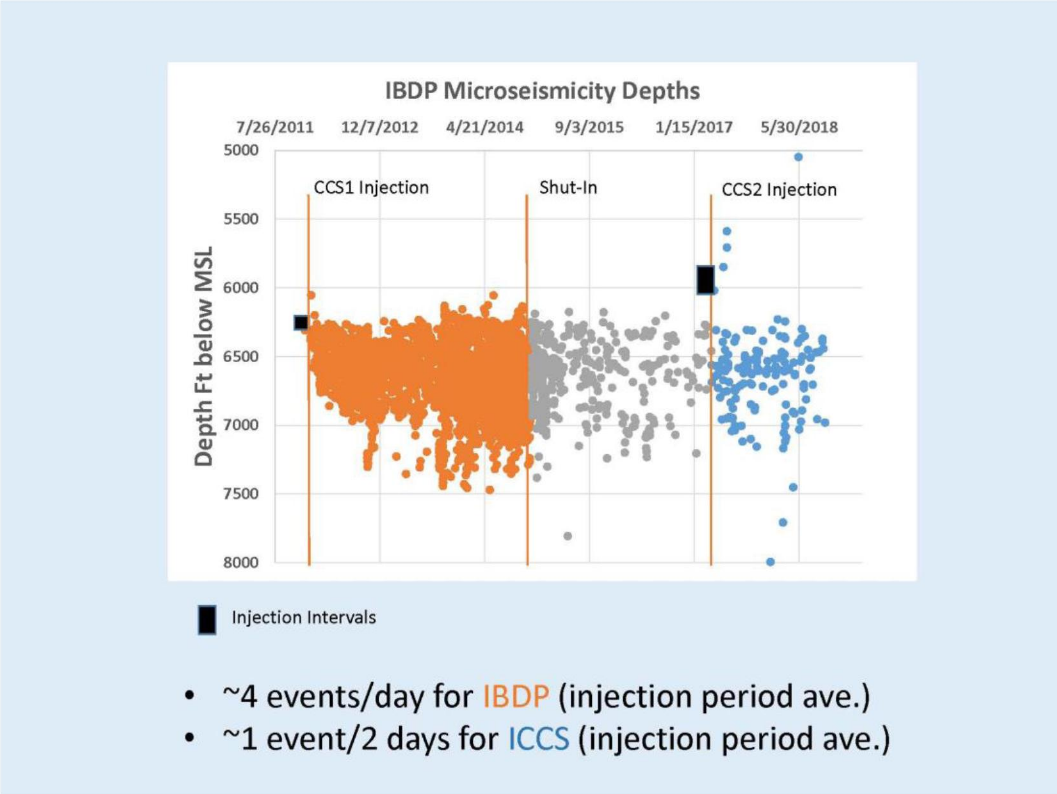


圖 5 兩期灌注計畫時間軸與地震發生深度圖

該報告結論如下：

1. CCS1 的井下灌注壓力為岩石破裂壓力的 73%。
2. VW1 監測井在蓋層下部測得最大孔隙壓力增加為 5.2%。
3. 第 1 期計畫中沒有要求微震監測，第 2 期計畫有要求施做。
4. 微震群都沿著既有的斷層發生，而這些斷層的幾何形貌可以從區域地殼應力推測出來。
5. 2 期灌注都無引發有感地震，所有地震規模介於負 2.13 至正 1.17 之間，約 95%為 0 或負值，85%的地震發生於比儲集層更深的地層中。
6. 該計畫採用與頁岩氣開採相同的地震規模警示系統，即地震規模

<0 無須注意，0<=地震規模<0.5 需警戒，地震規模>=0.5 需暫停灌注。

(2) Recent results of Tomakomai CCS demonstration project. Yoshihiro Sawada, JCCS, Japan.

本報告由日本 JCCS 公司發表，主要說明日本北海報苫小牧試驗灌注計畫在 2018 年 9 月 6 日北海道規模 6.7 地震發生後，井下環境並無受到影響。該地震震央位於灌注場址之 30 公里外，震源深度為 37 公里，震源距場址之直線距離為 47 公里，地震時場址受到最大加速度為 158 gal，相當於中央氣象局定義之 5 級地震(圖 6)。

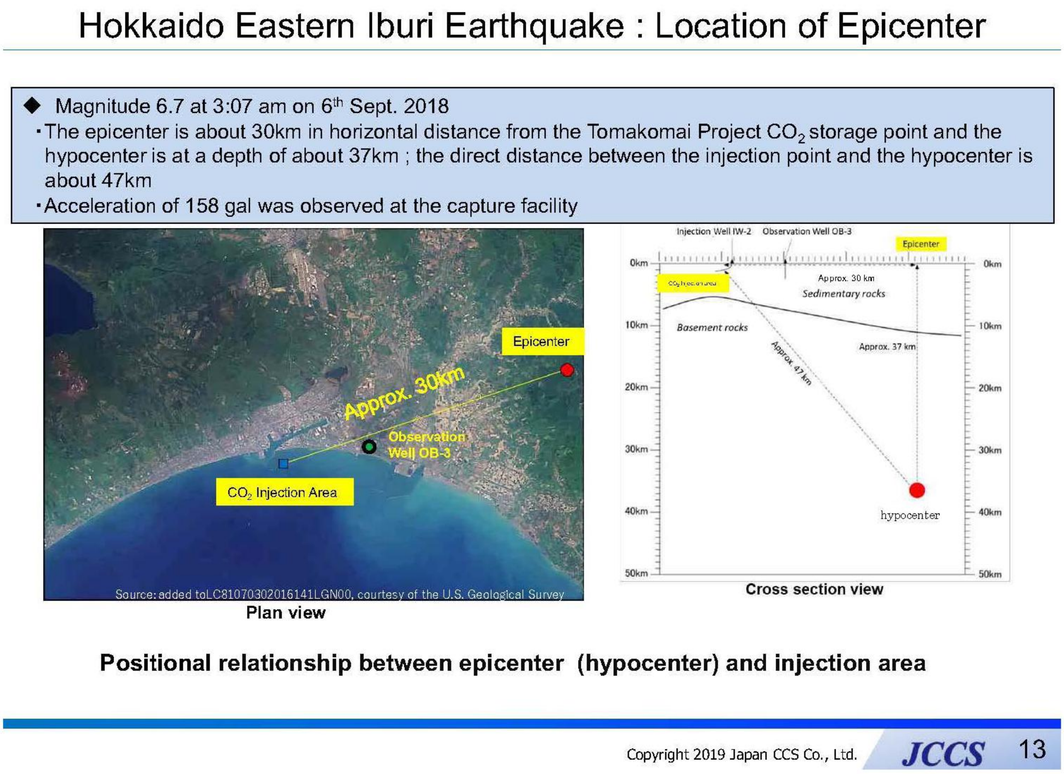


圖 6 2018 年 9 月北海道地震資訊

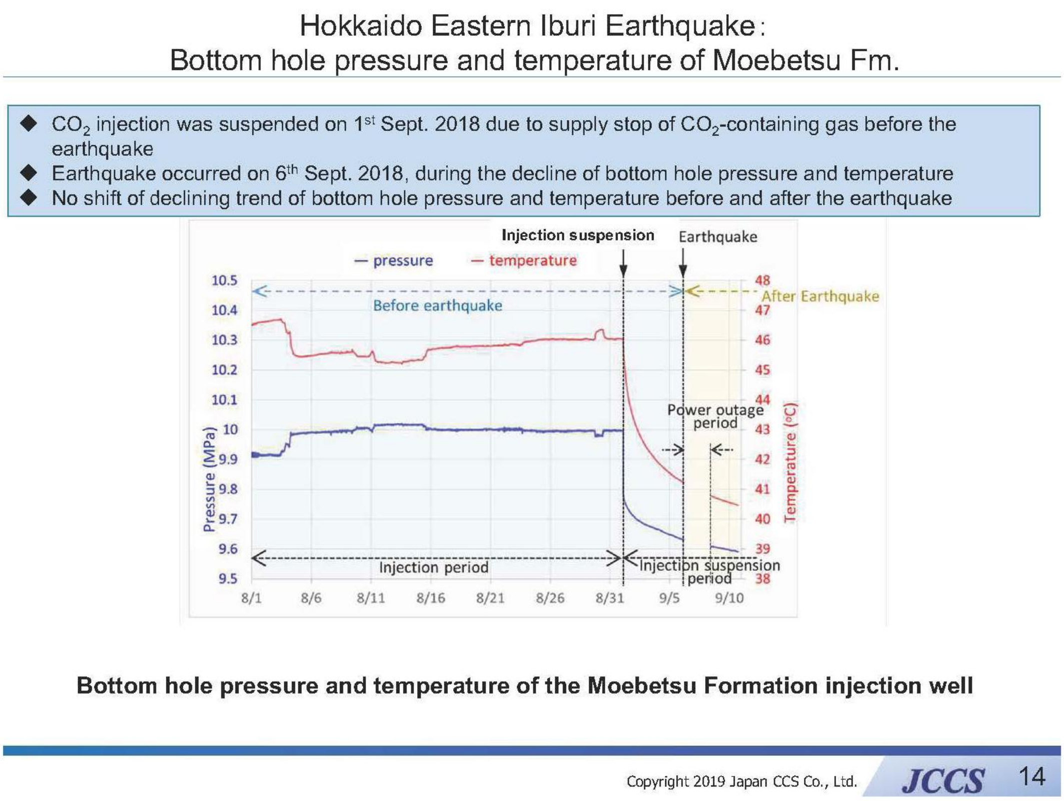


圖 7 2018 年 9 月北海道地震前後二氧化碳灌注資訊

在 2018 年 9 月北海道地震發生前，苫小牧灌注場就因為二氧化碳來源暫時停止，所以於 9 月 1 日即暫停灌注，從圖 7 的溫度與壓力圖可得知，停止灌注後，井下之溫度與壓力均開始減少。而 9 月 6 日地震發生後，該灌注場址發生短暫之停電，使得連續監測紀錄停止，但復電之後的監測資料可與斷電前之監測資料進行良好之比對，代表停電期間並無發生二氧化碳洩漏之情事。也因為資料連續性良好，因此 JCCS 公司亦對外表示地震並無影響到該灌注計畫。

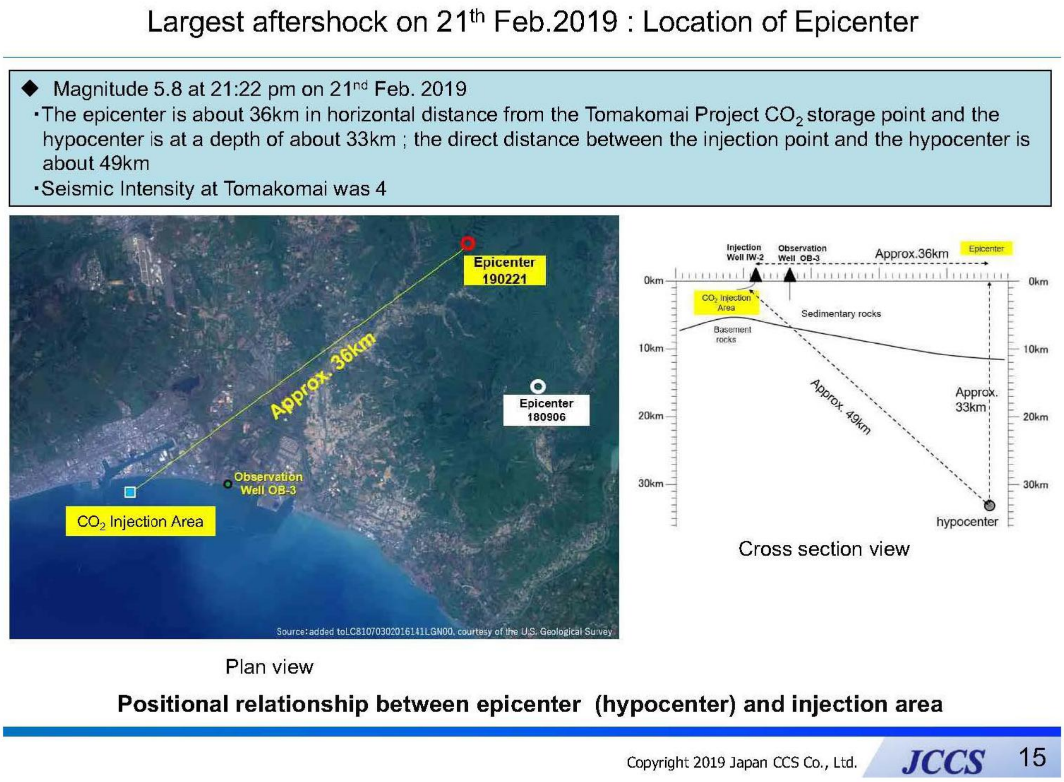


圖 8 2019 年 2 月北海道地震資訊

在 2019 年 2 月 21 日時，在接近 2018 年 9 月地震之區域發生了規模 5.8 之強烈餘震。該地震震央位於灌注場址之 36 公里外，震源深度為 33 公里，震源距場址之直線距離為 49 公里，地震時場址感受到 4 級地震(圖 8)。地震發生前後之井下溫度與壓力均無劇烈之變化，因此再次證明地震對於苫小牧之灌注工程影響有限(圖 9)。

從灌注區域附近微震發生次數可知，本區位處地震安靜區，灌注前僅 9 次微震，規模落於-0.09 至 0.24 間，深度為 5.9 至 8.6 公里間。灌注後僅 3 次微震，規模落於 0.31 至 0.52 間，深度為 7.4 至 7.7 公里間。在 2018 之主震與 2019 之最大餘震發生前後，該區都沒有發生任何微震，因此也代表灌注區域之地殼應力並沒有明顯改變(圖 10)。

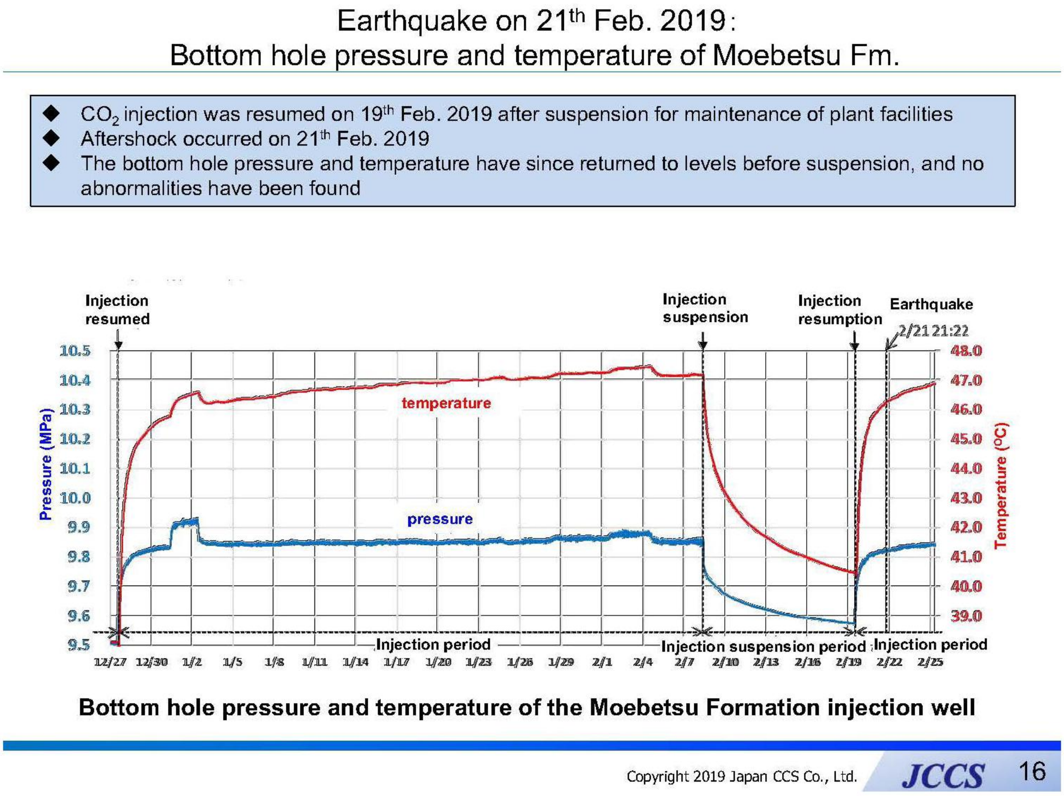


圖 9 2019 年 2 月北海道地震前後二氧化碳灌注資訊

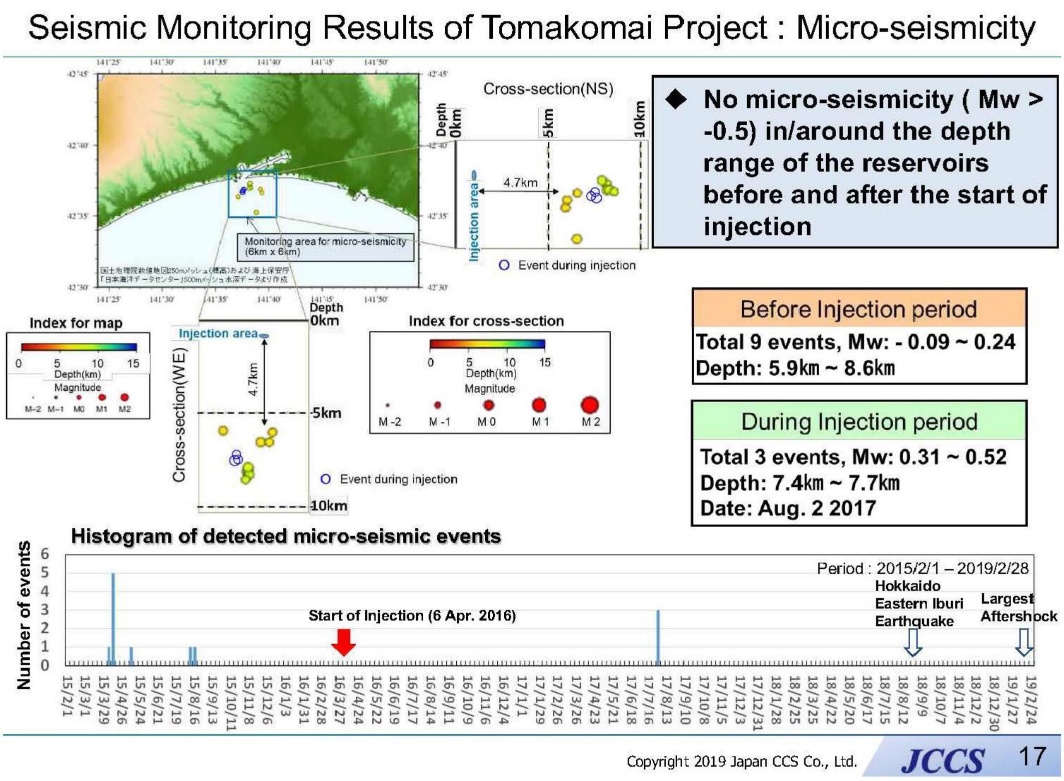


圖 10 苫小牧灌注區域 2015 年至 2019 年微震監測紀錄

(3) Injection, measurement, monitoring and verification at Aquistore: lessons learned by doing. Erik Nickel, Petroleum Technology Research Center, Canada.

本報告由加拿大石油科技研究中心發表，主要說明加拿大 Boundary Dam 電廠附近之 Aquistore 二氧化碳地質封存計畫之監測手段，該計畫共使用了 30 種監測方法，分為地表監測與地下監測。地表監測分為二氧化碳團塊監測、地表變形監測、以及二氧化碳洩漏監測。二氧化碳團塊監測分為 3D 震測、地震儀陣列、大地電磁、以及重力等四種監測方法。地表變形監測分為被動地震觀測、合成孔徑雷達干涉、全球衛星定位系統、以及測傾管。二氧化碳洩漏監測分為地下水與土壤氣監測、以及碳同位素剖面。地下監測分為跨井震測與 VSP、跨井與地表聯測大地電磁、即時井下溫度壓力、井下地震儀、井下流體取樣、定期井下電測、井下光纖溫度測量、以及井下重力測量(圖 11)。

由於該計畫是將二氧化碳注入深部鹽水層中，因此在灌注時發現了鹽結晶的問題，由於鑽井階段並無產生結晶鹽，因此該團隊認為結晶鹽的產生應與超臨界二氧化碳灌注有關，然而鹽的生成會影響井下儀器之操作，更甚者會加速井下套管之腐蝕，因此該團隊目前正加緊找出結晶鹽的成因(圖 12)。台灣目前規劃之二氧化碳地質封存與 Aquistore 均為地下深部鹽水層封存，因此未來亦可能面臨類似之結晶鹽問題，本所將持續關注 Aquistore 於相關議題之研究進度。

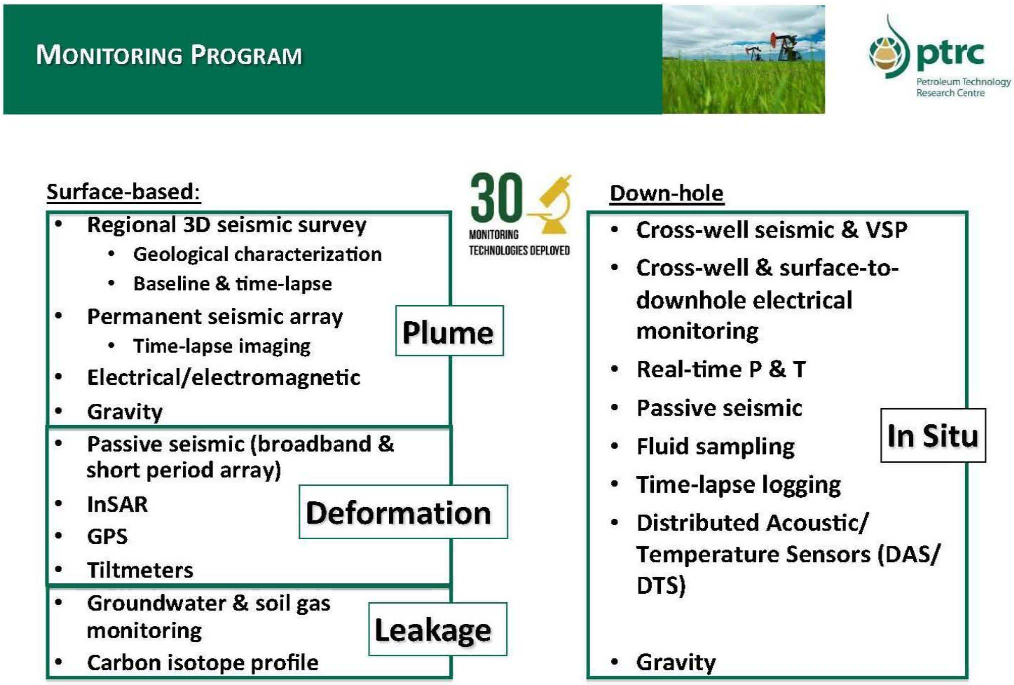


圖 11 Aquistore 計畫所使用之監測方法

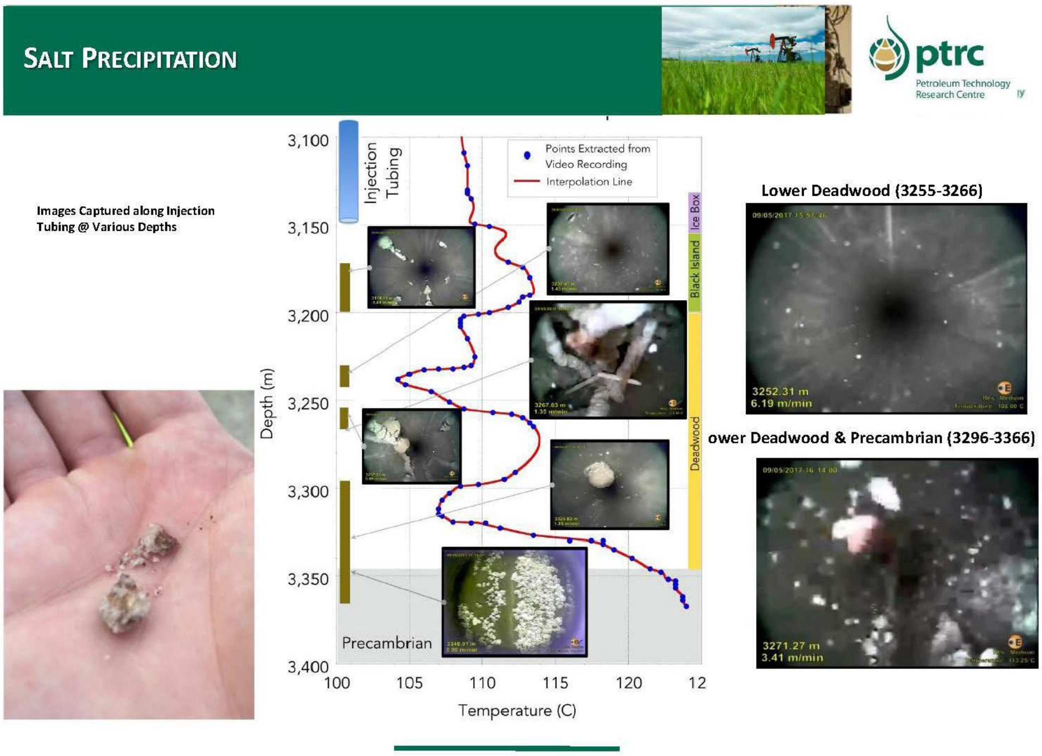


圖 12 Aquistore 計畫所面臨之結晶鹽問題

該報告結論如下：

1. 選址並非全部為科學議題。

2. 監測程度與時機取決於很多變數。

3. 井下監測系統常常失效。

4. 灌注超臨界二氧化碳與結晶鹽析出之關聯性仍然無解。

5. 詳細之監測計畫需要財力雄厚之企業才能維持。

(4) The convergence of modelling and monitoring: reviewing conformance at Sleipner using geophysical data. Jim White, British Geological Survey, UK.

本報告由英國地質調查所發表，主要說明 Sleipner 灌注計畫目前已知二氧化碳分布於 9 個儲集層中(圖 13)，而位於最頂部的儲集層之二氧化碳分布亦越來越廣(圖 14)。

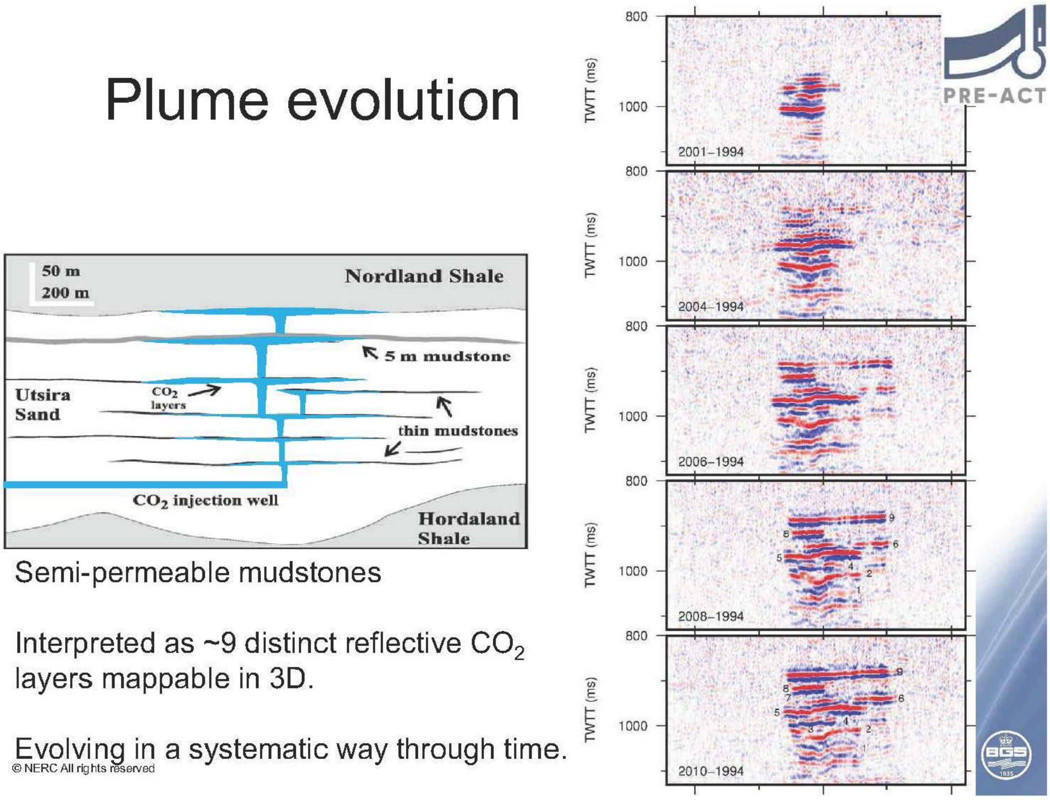


圖 13 Sleipner 灌注計畫自 1994 年起之二氧化碳團塊垂直遷徙變化

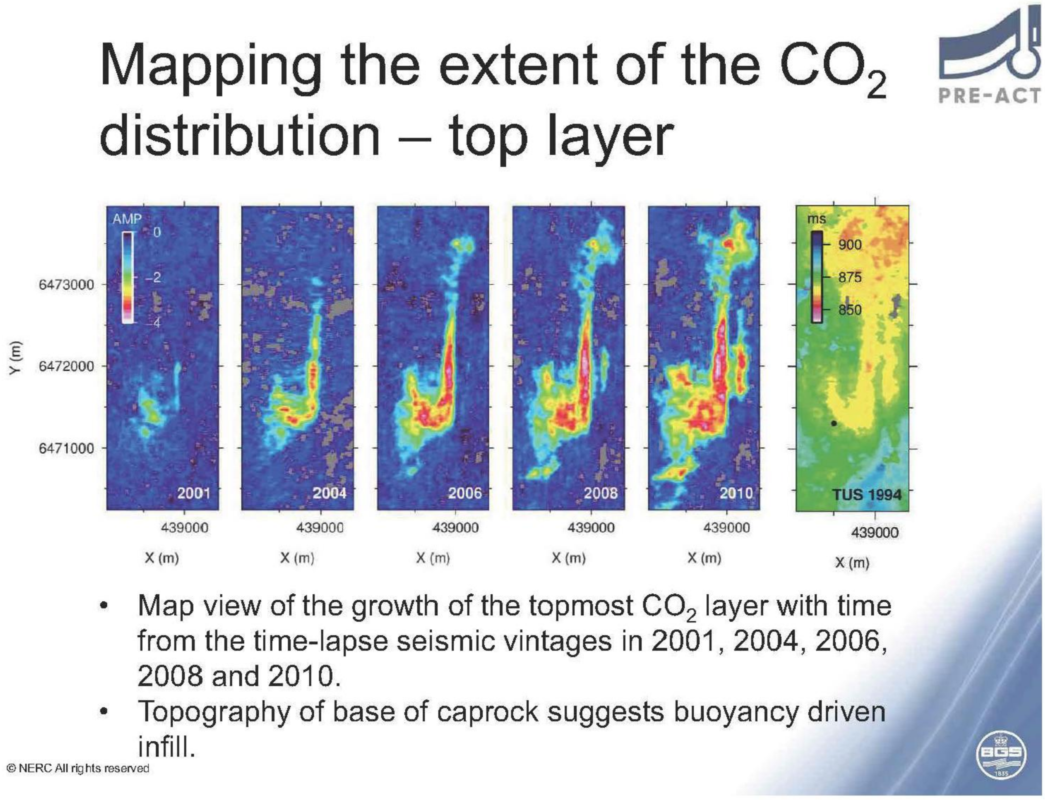


圖 14 Sleipner 灌注計畫自 1994 年起之二氧化碳團塊水平遷徙變化

(5) Tackling industrial emissions in The Netherlands: the role of CCS. Joëlle Rekers, Ministry of Economic Affairs and Climate, The Netherlands.

本報告由荷蘭經濟與氣候部發表，主要說明荷蘭的減碳策略在 2017 年訂定，該國目標為 2030 年時減去 4870 萬噸之二氧化碳，同年並關閉所有燃煤電廠，且於該年起，所有新車均為電動車(圖 15)。荷蘭同時做出了 CCS 在該國產業界的定位，首先是僅於工業界(鋼鐵、煉油、製氫、肥料、垃圾焚化等)使用 CCS 進行減碳，且不使用於燃燒後捕獲的火力發電業，但燃燒前捕獲的製氫業或生質燃料發電則有發展的潛力。目前荷蘭的二氧化碳再利用部分會專注於農業溫室，而

未來荷蘭僅會進行離岸二氧化碳地質封存，儲集量預估為 17 億噸(圖 16)。

圖 15 荷蘭 2017 年訂定之減碳目標

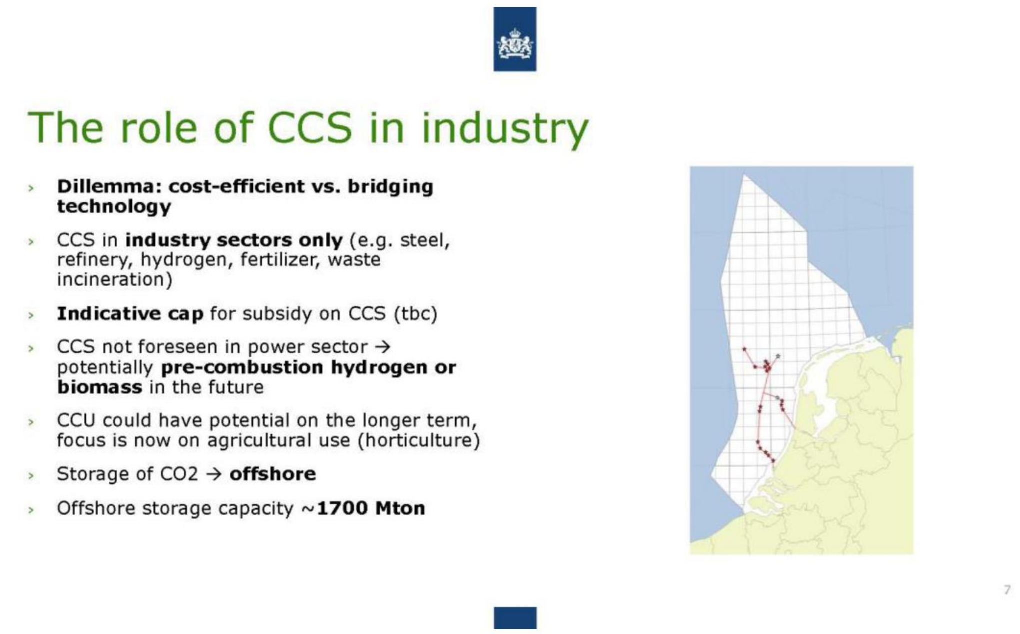


圖 16 荷蘭規劃之 CCS 發展方向

(6) The public good case for European CO_2 transport & storage networks Jonas Helseth, Bellona, Norway.

本報告由挪威 Bellona 基金會發表，主要說明挪威建議的二氧化

碳地質封存策略，與荷蘭相同的是，挪威亦認為未來歐洲二氧化碳地質封存之方向要朝離岸封存發展，並指出要在歐洲設置數個二氧化碳輸出港(圖 17)。

圖 17 挪威 Bellona 基金會建議歐洲離岸碳封存與碳輸出港之地點

(7) Building a European CO_2 transport network - Porthos project. Bram Herfkens, EBN - Port of Rotterdam, The Netherlands.

本報告由荷蘭鹿特丹港務局發表，由於目前歐洲已有荷蘭與挪威決定進行離岸二氧化碳地質封存，因此鹿特丹港務局提出增加二氧化碳輸出設備於該港之中，並輔以橫跨歐洲之二氧化碳輸送管線，使該港成為歐陸最大的二氧化碳輸出港(圖 18)。除二氧化碳輸出設備之外，鹿特丹港務局亦規劃管線至該市之溫室，作為二氧化碳再利用之用途，達到循環經濟之目的。

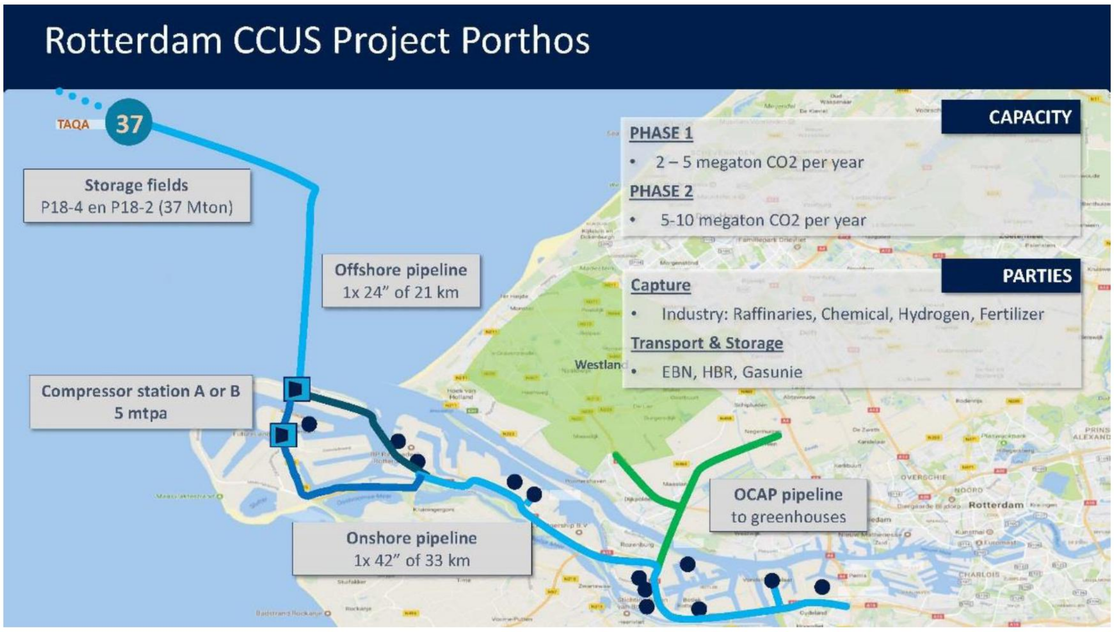
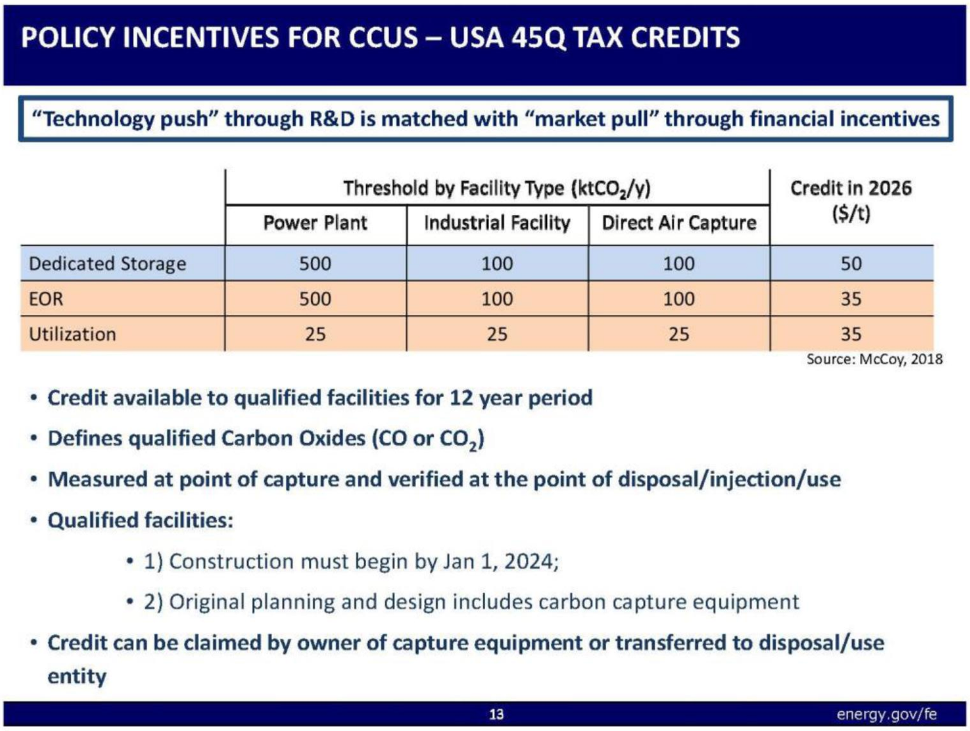


圖 18 鹿特丹港務局規劃之二氧化碳管線與輸出港示意圖

(8) Carbon utilization challenges and opportunities. Mark Ackiewicz, Department of Energy, US.

本報告由美國能源部發表，主要說明美國最新的 45Q 減稅方案。該方案之目的為鼓勵企業進行 CCS 或 CCU，因此訂定出若於 2024 年之前完成二氧化碳捕獲至地質封存、或至油氣增產(EOR)、或至再利用等其中之一程序，即可獲得減稅。該減稅方案亦規定，此減稅條約只會執行 12 年，而依據二氧化碳的處置方式不同而有不同的減稅率，同時減稅資格也會依照不同的處置方式而有所不同(圖 19)。減稅稅率以地質封存為最多(每噸 50 元)，再利用為最少(每噸 35 元)。取得減稅資格門檻以發電廠為最多(每年 50 萬噸)，再利用為最少(每年 2 萬 5 千噸)。若此減稅方案成功引導大型企業進行 CCS 或 CCU，則美國生產之產品可降低碳足跡，即便未來歐盟要實施全面碳稅課徵，美國之產品亦有競爭力。



POLICY INCENTIVES FOR CCUS – USA 45Q TAX CREDITS

"Technology push" through R&D is matched with "market pull" through financial incentives

	Threshold by Facility Type (ktCO$_2$/y)			Credit in 2026 ($/t)
	Power Plant	Industrial Facility	Direct Air Capture	
Dedicated Storage	500	100	100	50
EOR	500	100	100	35
Utilization	25	25	25	35

Source: McCoy, 2018

- Credit available to qualified facilities for 12 year period
- Defines qualified Carbon Oxides (CO or CO_2)
- Measured at point of capture and verified at the point of disposal/injection/use
- Qualified facilities:
  - 1) Construction must begin by Jan 1, 2024;
  - 2) Original planning and design includes carbon capture equipment
- Credit can be claimed by owner of capture equipment or transferred to disposal/use entity

13 energy.gov/fe

圖 19 美國 45Q 減稅條款說明

(9) Carbon Capture and Storage promotion in Taiwan. Chung Huang, TCCSUA and Taiwan Power Company, Taiwan

本次論壇中，本公司亦指派黃鐘地質研究專員報告本公司 CCS 相關研究執行進度(圖 20)，報告內容如圖 21 至 32 所示。

圖 20 黃專員於 CO_2GeoNet 公開論壇報告本公司 CCS 相關研究進度

圖 21 報告封面

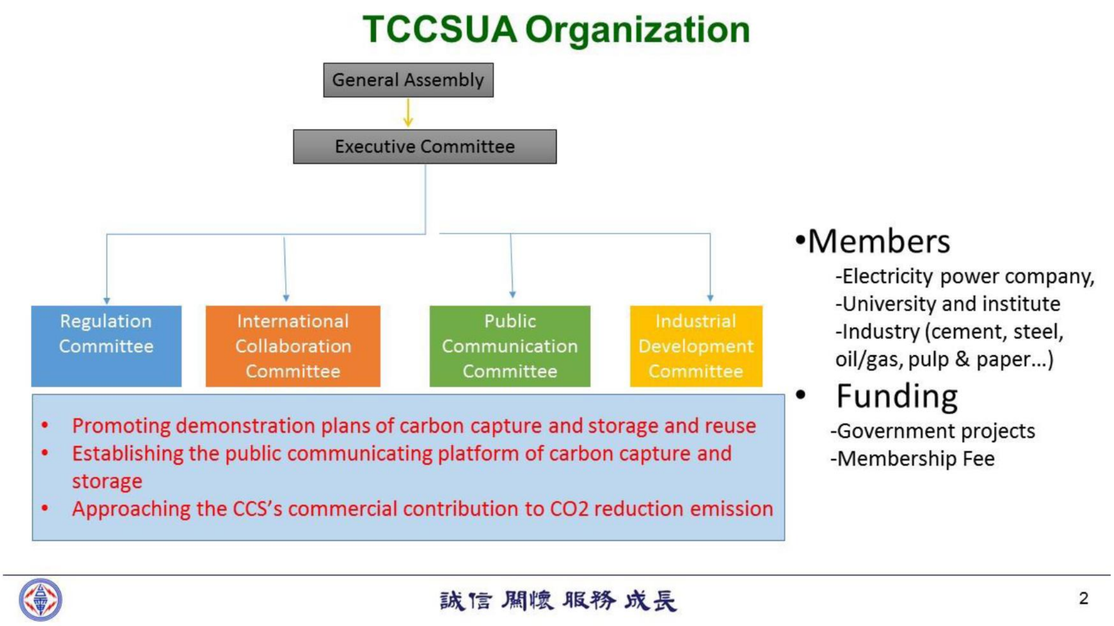


圖 22 臺灣碳捕存與再利用協會(TCCSUA)組織架構簡介

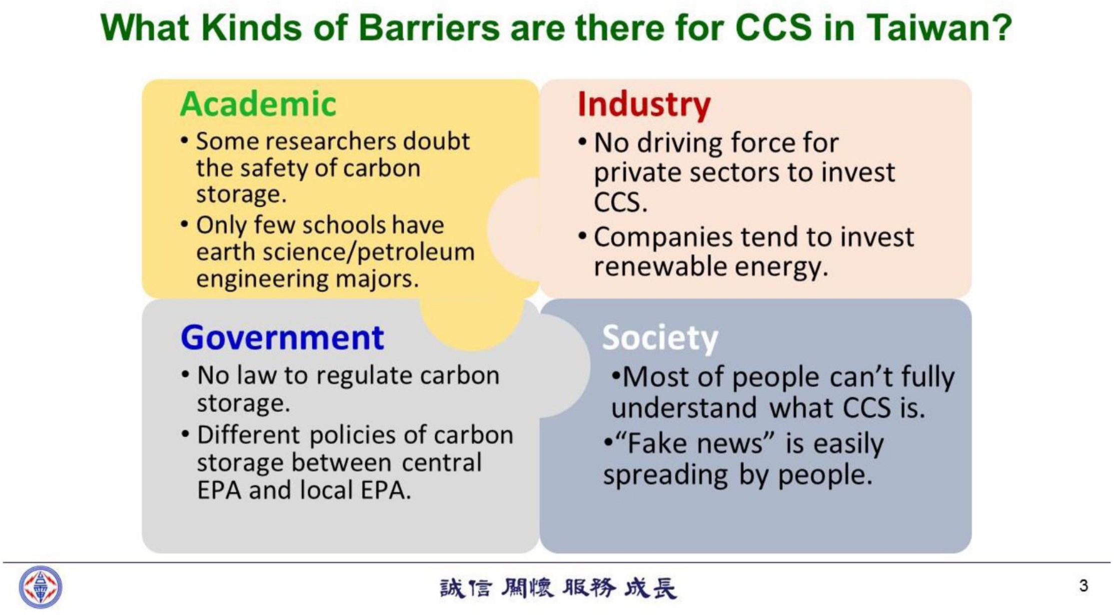


圖 23 台灣 CCS 面臨之困境

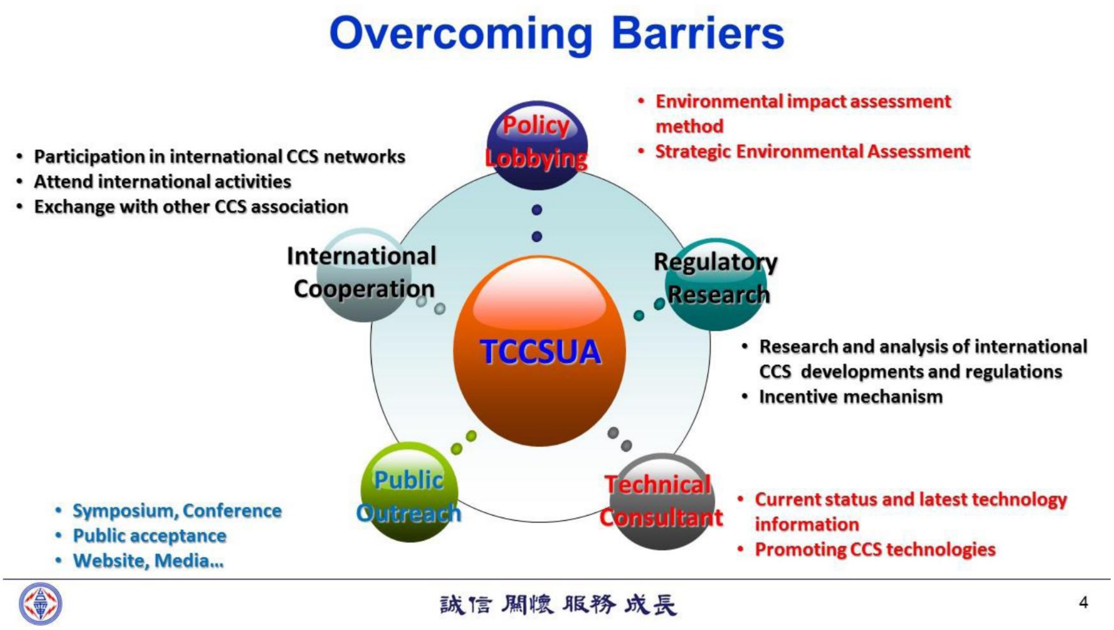


圖 24 克服目前面臨 CCS 困境之解決方案

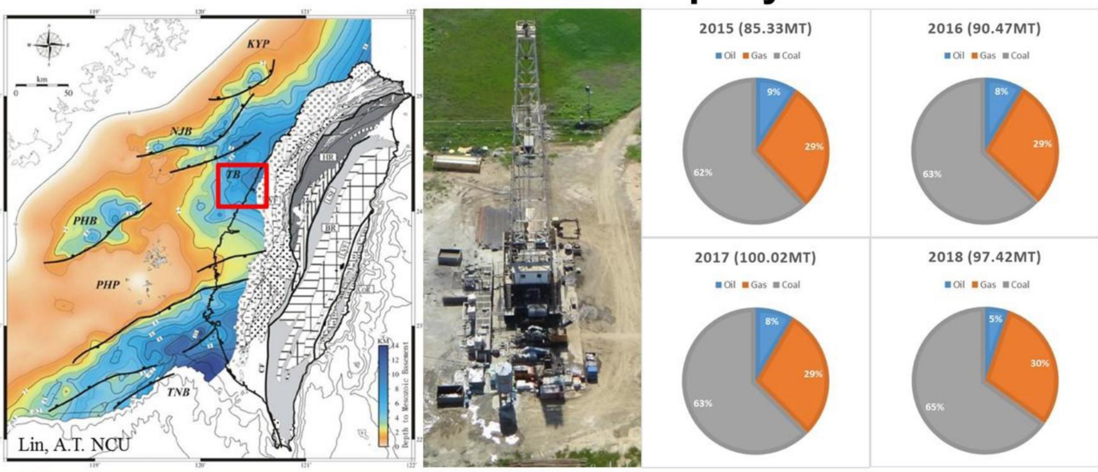
Key stakeholders and engagement

- The key stakeholders your association needs to engage with in your country in order to drive CCS forward?
  - Environmental Protection Administration, both central and local.
  - Non-governmental organization and local communities.
  - Enterprise, both state-owned and private sectors.
- Recent and upcoming stakeholder engagement activities
  - Inviting NGO to visit CCS site in Japan.
  - Inviting electronic and semiconductor industry to join carbon offset project.
  - Getting support from government for speeding up the construction of pilot capture plant.

誠信 關懷 服務 成長 5

圖 25 利害關係人與其參與方案

Current Status of Carbon Storage Research of Taiwan Power Company



誠信 關懷 服務 成長 6

圖 26 本公司碳封存計畫簡介

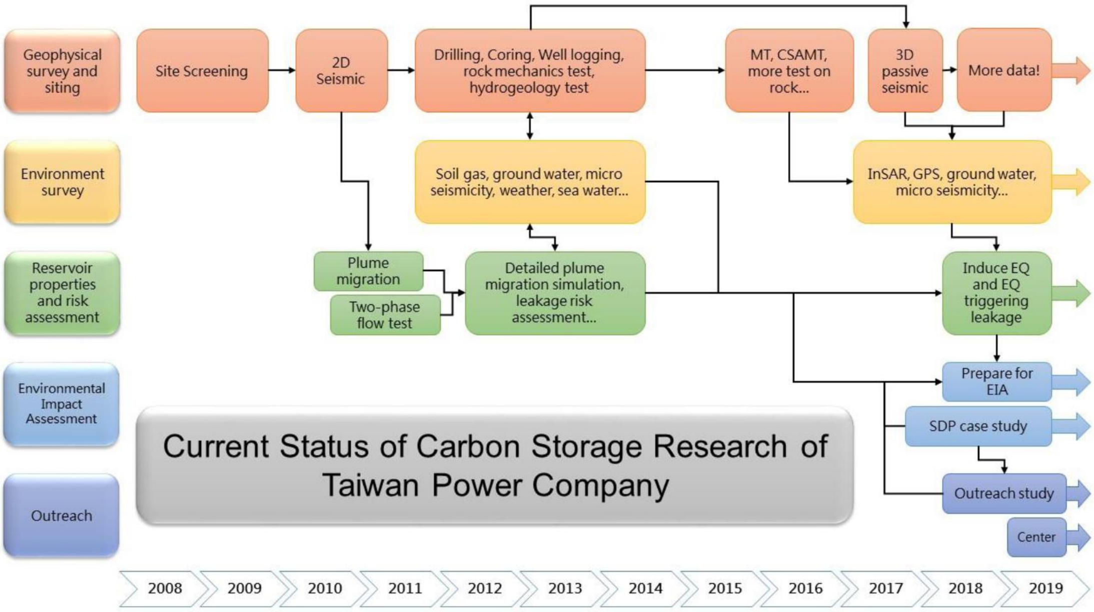


圖 27 本公司 CCS 研究路徑圖

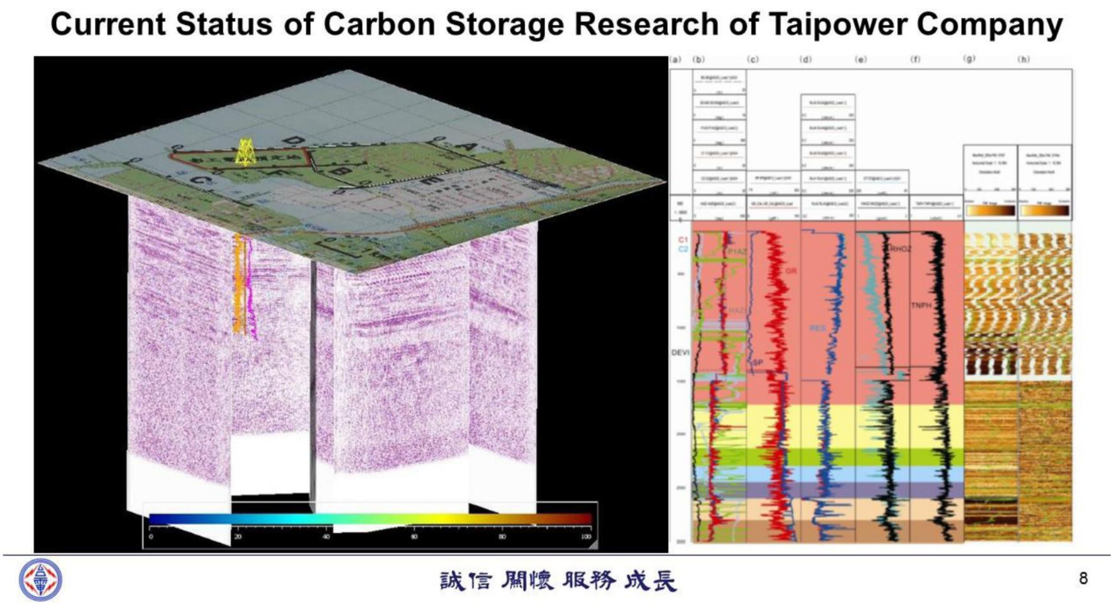


圖 28 彰濱工業區地下地質資料展示

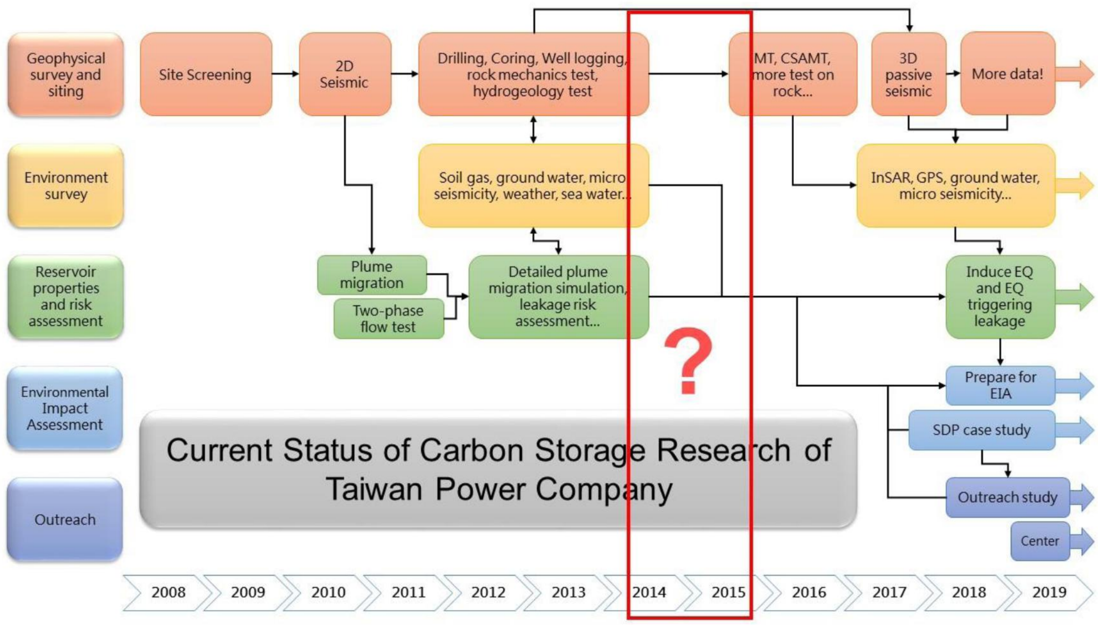


圖 29 說明 2014-2015 年 CCS 相關研究暫緩進行之原因

圖 30 民眾對於 CCS 仍有質疑

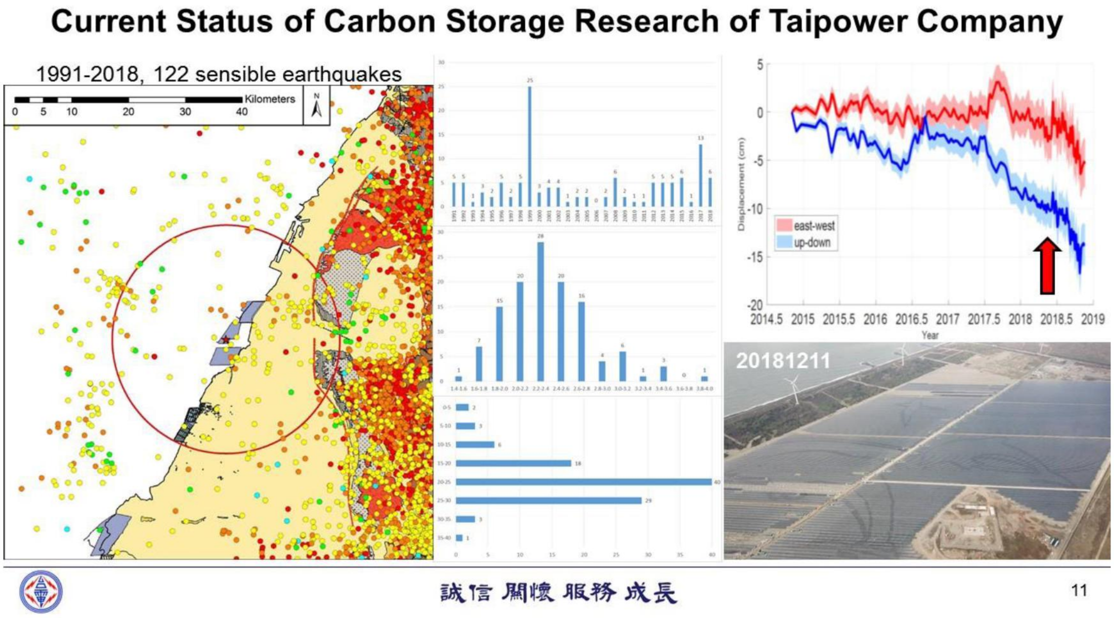


圖 31 本公司於彰濱工業區進行地震與地形變化監測之成果

圖 32 封底

貳、考察行程

一、 亥姆霍茲地球科學研究中心簡介

本次考查地點為位在德國波茲坦之亥姆霍茲地球科學研究中心(GFZ German Research Centre for Geosciences，圖 33)，該中心成立於 1992 年，主要研究方向可分為五個主軸：地球動力學、板塊系統、地表與氣候交互作用、天然災害、地質資源與能源。目前該中心的學術執行長為 Reinhard Hüttl 博士，中心組織依照研究人員的專長區分為四個研究部門(Department)，分別為大地測量、地球物理、地球化學、以及地球系統學等，每個研究部門底下再分為四到八個不等之研究室(Section)，每個研究室之人力約為 20 至 30 人。除此之外，該中心尚有數個行政支援單位與跨部門研究計畫，其組織圖詳如圖 34。

由 GFZ 公布之截至 2018 年 12 月 31 號的資料之中得知(https://www.gfz-potsdam.de/en/about-us/organisation/facts-and-figures/)，該中心共有 1281 名員工，其中 800 人為科學家、技術人員、以及行政人員，102 名助理與學生，299 名訪問學者。該中心 2018 年的經費有 6,500 萬歐元(約 22.7 億新台幣)來自德國政府，其中 90%的經費來自於德國聯邦教育與研究部，10%來自於布蘭登堡邦科學、研究與文化部。此外，該中心亦有 3,000 萬歐元(約 10.5 億新台幣)之經費來自其他單位，如印尼 Pertamina 石油公司之地熱發電子公司即與該中心

地質能源研究室合作，在印尼北蘇拉威西省興建地熱發電廠。

圖 33 亥姆霍茲地球科學研究中心行政大樓外觀與研究園區門牌

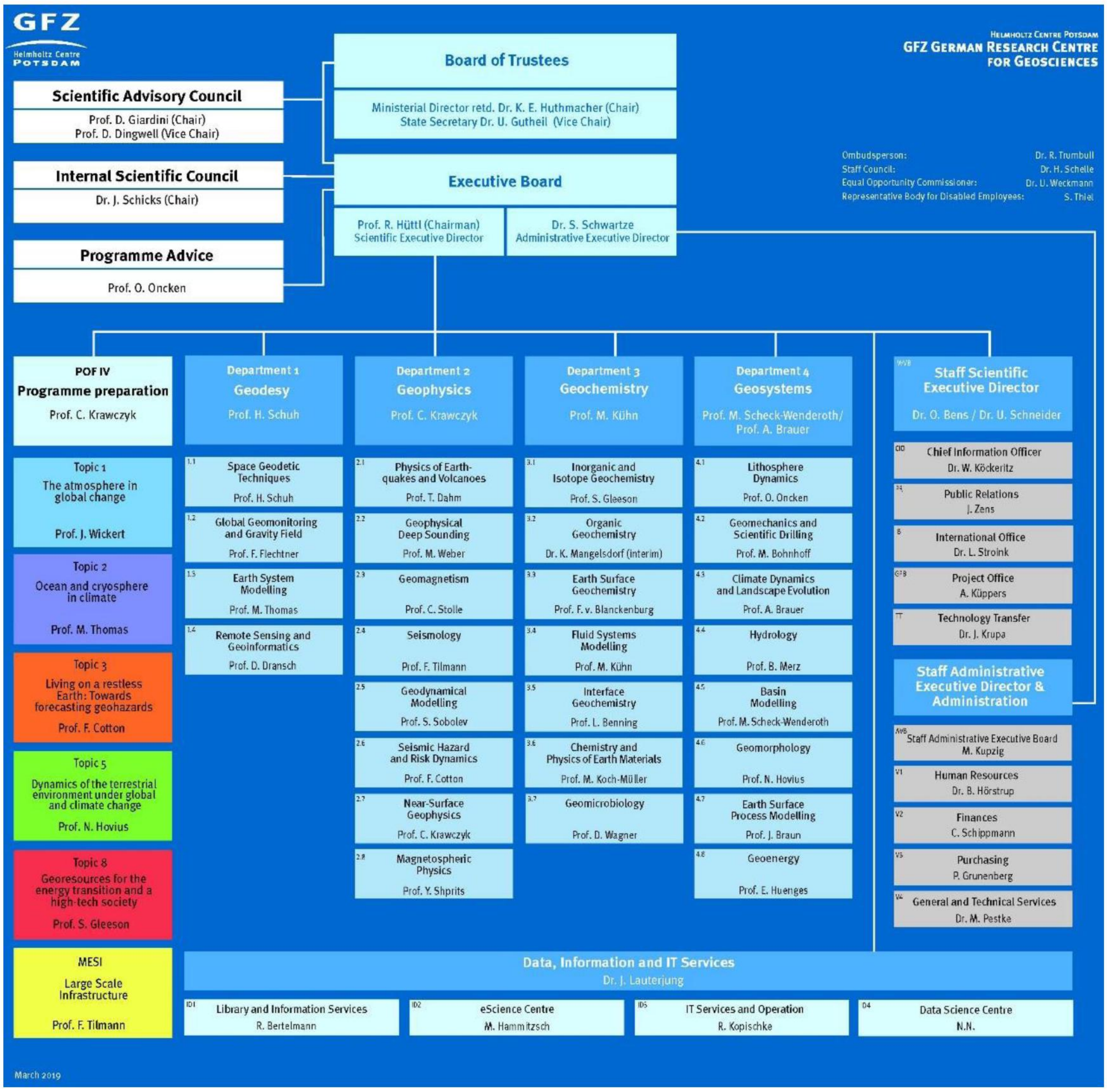


圖 34 GFZ 組織圖

二、 地球動力學部地質能源研究室考察

本次考查是經由地球系統學部地形研究室主任 Niels Hovius 之牽線，獲得該部之邀請並前往該部地質能源研究室訪問。地質能源研究室主要由 Maren Brehme 博士負責接待與說明，在拜會地質能源研究室時，特別針對該研究室目前所進行之研究計畫進行了解，希望藉由討論之過程獲得地熱發電探勘、規劃、以及營運等相關資訊。

(1) 地質能源研究室研究業務簡介

GFZ 地質能源研究室可執行之業務與該研究室製作之簡介如下：

1. 地溫梯度調查(圖 35、36)

   利用井下電測資料、地球物理探勘資料、以及岩石物理特性模式建立地下熱流模型推估整個歐洲的地溫環境。

2. 岩石物理性質分析(圖 37、38)

   利用岩石破壞試驗、二相流試驗、以及電子顯微鏡觀察等方式取得岩石樣本之熱傳、滲透率等資料。

3. 熱液特性分析(圖 39、40)

   分析熱液之物理及化學性質。

4. 儲集層監測(圖 41、42)

   利用地表地球物理方法與井下光纖監測儲集層之溫度與壓力等數據，作為產量預估之依據。

5. 儲集層工程(圖 43、44)

   利用數值模擬的方法評估儲集層開發程序。

6. 電廠規劃與建工程(圖 45、46)

   整合電力、機械、鑽井工程、儲集層工程與地球科學相關資訊作為地熱電廠興建之基本資料。

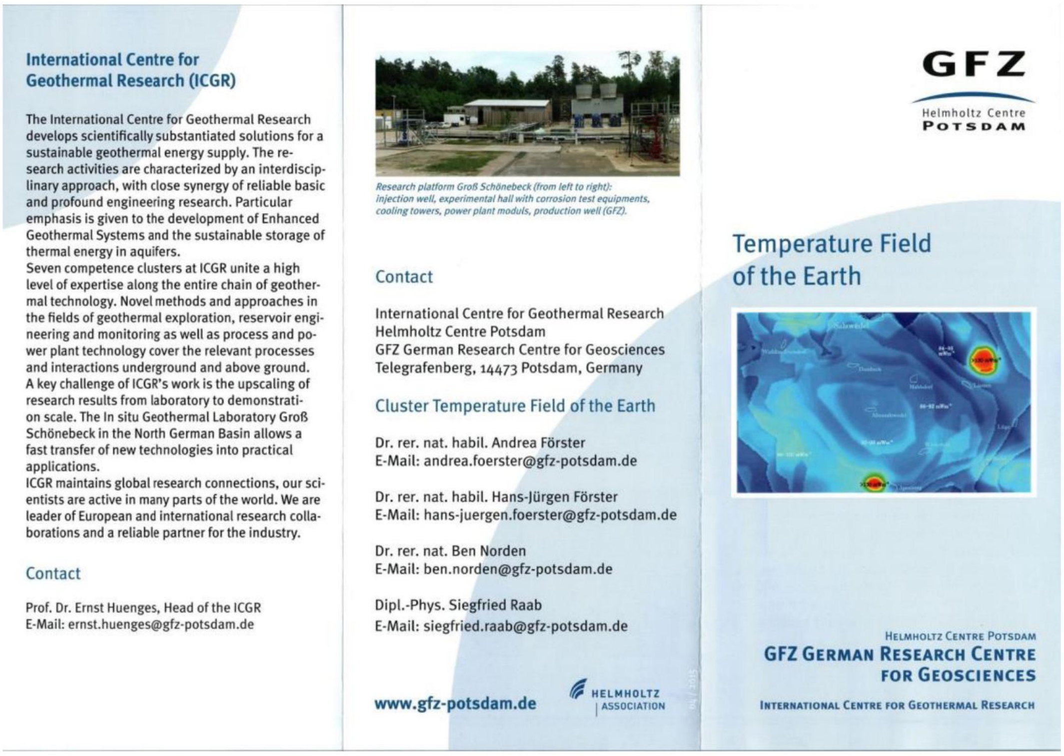


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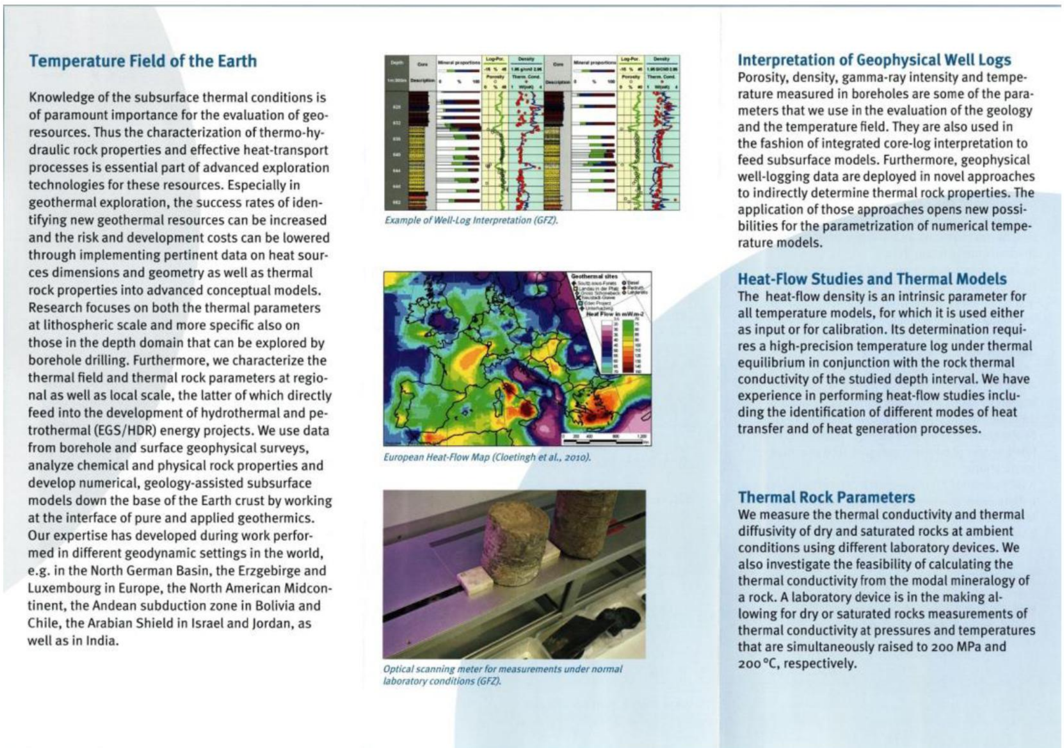
圖 35 GFZ 地質能源研究室地溫梯度調查簡介(I)



Temperature Field of the Earth

Knowledge of the subsurface thermal conditions is of paramount importance for the evaluation of georesources. Thus the characterization of thermo-hydraulic rock properties and effective heat-transport processes is essential part of advanced exploration technologies for these resources. Especially in geothermal exploration, the success rates of identifying new geothermal resources can be increased and the risk and development costs can be lowered through implementing pertinent data on heat sources dimensions and geometry as well as thermal rock properties into advanced conceptual models. Research focuses on both the thermal parameters at lithospheric scale and more specific also on those in the depth domain that can be explored by borehole drilling. Furthermore, we characterize the thermal field and thermal rock parameters at regional as well as local scale, the latter of which directly feed into the development of hydrothermal and petrothermal (EGS/HDR) energy projects. We use data from borehole and surface geophysical surveys, analyze chemical and physical rock properties and develop numerical, geology-assisted subsurface models down the base of the Earth crust by working at the interface of pure and applied geothermics. Our expertise has developed during work performed in different geodynamic settings in the world, e.g. in the North German Basin, the Erzgebirge and Luxembourg in Europe, the North American Midcontinent, the Andean subduction zone in Bolivia and Chile, the Arabian Shield in Israel and Jordan, as well as in India.

Example of Well-Log Interpretation (GFZ).

European Heat-Flow Map (Cloetingh et al., 2010).

Optical scanning meter for measurements under normal laboratory conditions (GFZ).

Interpretation of Geophysical Well Logs

Porosity, density, gamma-ray intensity and temperature measured in boreholes are some of the parameters that we use in the evaluation of the geology and the temperature field. They are also used in the fashion of integrated core-log interpretation to feed subsurface models. Furthermore, geophysical well-logging data are deployed in novel approaches to indirectly determine thermal rock properties. The application of those approaches opens new possibilities for the parametrization of numerical temperature models.

Heat-Flow Studies and Thermal Models

The heat-flow density is an intrinsic parameter for all temperature models, for which it is used either as input or for calibration. Its determination requires a high-precision temperature log under thermal equilibrium in conjunction with the rock thermal conductivity of the studied depth interval. We have experience in performing heat-flow studies including the identification of different modes of heat transfer and of heat generation processes.

Thermal Rock Parameters

We measure the thermal conductivity and thermal diffusivity of dry and saturated rocks at ambient conditions using different laboratory devices. We also investigate the feasibility of calculating the thermal conductivity from the modal mineralogy of a rock. A laboratory device is in the making allowing for dry or saturated rocks measurements of thermal conductivity at pressures and temperatures that are simultaneously raised to 200 MPa and 200 °C, respectively.

圖 36 GFZ 地質能源研究室地溫梯度調查簡介(II)

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Rock Physics

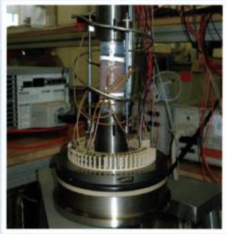

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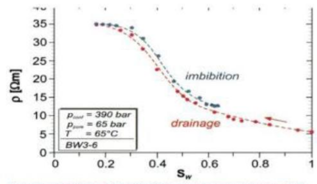
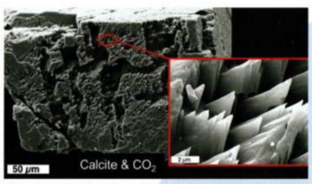
圖 37 GFZ 地質能源研究室岩石物理性質分析簡介(I)

Rock Physics

Scientific themes within the research cluster "Rock Physics" relate to interrelations between physical properties of rock and its inner structure. In addition to characterizing a rock's actual state investigations on dynamic processes and time-dependent physical changes are conducted. The research topics we address result from sustainable use of geothermal energy, carbon dioxide sequestration, and the use of natural methane hydrate deposits.
The working group has an experimental orientation and possesses several laboratories, wherein simultaneous measurements and experiments can be performed on the parameters permeability, electrical conductivity, and P and S-wave velocities. Our rock physical laboratories are equipped with unique apparatuses that can handle highly corrosive reservoir fluids and that can be operated at controlled pressure and temperature conditions encountered during use of geological reservoirs.
Principal research topics in rock and hydrate physics include effects of dissolution-precipitation reactions on rock transport properties, two phase flow in geothermal reservoirs and during CO_2 sequestration as well as large scale electrical and seismic tomography of porous media during methane hydrate formation and decomposition.
Our experimental methodology is continuously developed further to conduct experiments at progressively more extreme, e.g. supercritical, conditions. Linking exploration and exploitation of geological reservoirs our scientific results contribute to their sustainable use.



Electrical conductivity of a reservoir sandstone measured at reservoir conditions as a function of water saturation (GFZ).



SEM micrograph of a calcite crystal after exposure to a synthetic formation fluid containing CO_2 at simulated reservoir conditions (GFZ).

Setup for measuring electrical conductivity of fluid saturated rock samples at up to 400 °C. A cylindrical furnace heats the specimen and aluminum cooling elements protect the sensors (GFZ).

Rock and reservoir characterization

Measurements of physical rock properties under simulated in situ conditions are central to an integrated characterization of geological reservoirs. On a routine basis we operate experimental apparatuses and devices to investigate seismic, electrical, and hydraulic properties of water-saturated rock samples at controlled confining pressures up to 300 MPa, pore pressures up to 100 MPa and maximum temperatures of 250 °C.

Fluid-rock interactions

Production and injection of fluids from and into the subsurface, respectively, yield changes in the thermodynamic and chemical state of a reservoir. As a consequence, fluid-rock interactions are induced that may alter the rock's physical properties. To predict the long-term behavior of reservoirs during and after use we conduct laboratory investigations at simulated reservoir conditions.

Development of methodologies

To cope with challenges of new research tasks existing methods are developed further and new experimental setups are constructed. Many unique apparatuses thus emerge capable of measuring a number of physical rock properties at simulated conditions of the earth's crust. A challenge, e.g., is the extension of the experimentally usable temperature range to 400 °C and beyond as encountered in ultra hot geothermal reservoirs.

圖 38 GFZ 地質能源研究室岩石物理性質分析簡介(II)

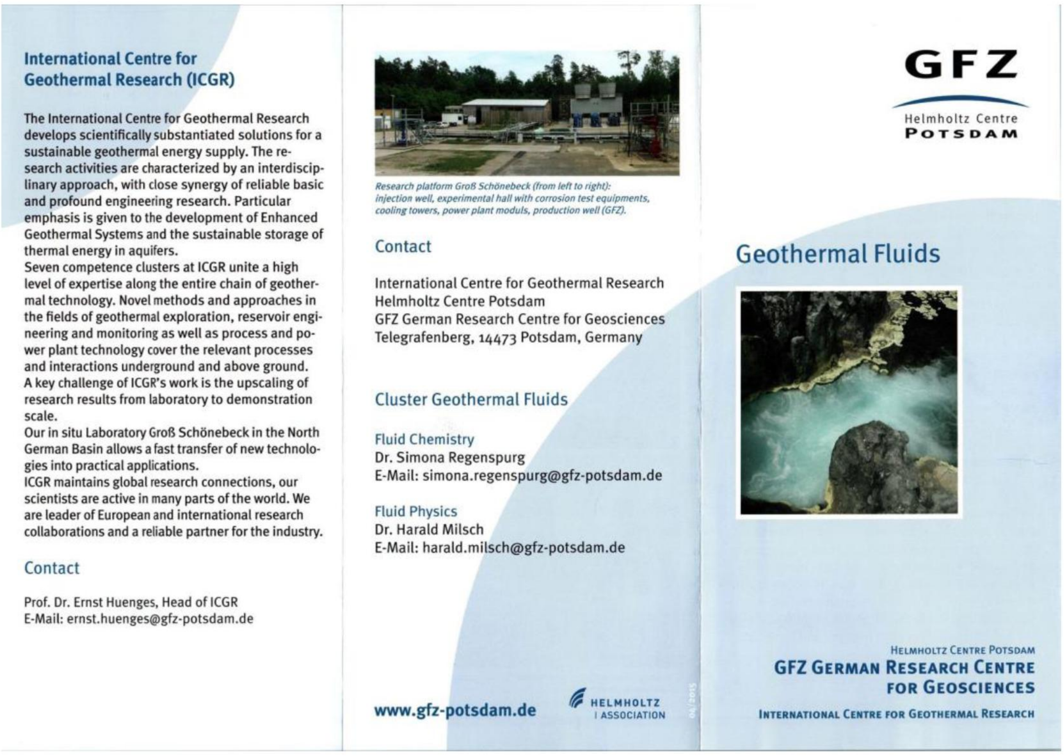


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圖 39 GFZ 地質能源研究室熱液特性分析簡介(I)

Geothermal Fluids

Geothermal fluids are the transport media for subsurface heat, and, therefore, the essential substance of geothermal energy production. They consist of a mixture of gas and condensed phases with complex chemical compositions. An exact understanding of the physical properties and chemical tendencies of these fluids are necessary for modeling the many processes occurring during fluid transport. Such models are required for minimizing risk and improving plant sustainability.
The research cluster "Geothermal Fluids" is involved in researching the chemical behavior and physical properties of geothermal fluids. The cluster is also responsible for online fluid and gas monitoring at the research platform Groß Schönebeck. The working group has an analytical-experimental orientation and possesses several laboratories, wherein measurements and experiments can be performed at in-situ reservoir conditions.
Principal research topics include the kinetics of dissolution and precipitation of minerals into and from a geothermal fluid, fluid-rock-materials interactions, and mixing rules for thermophysical fluid parameters. Furthermore, continuous progress is being made regarding methodological and technological developments of experimental techniques. Interdisciplinary work with other research groups at the ICGR is performed, for example, in the areas of corrosion and scaling, fluid-rock interactions and thermodynamic parameter determination for reservoir modeling. We research an assortment of topics in cooperation with several national and international project partners.

Siliceous precipitates (scales) within dismantled tubing of an Indonesian geothermal power plant (GFZ).

Laboratory for fluid physics (GFZ).

The online monitoring system "FluMo" at the research platform Groß Schönebeck, Germany (GFZ).

Fluid Chemistry

Mineral deposition in the components of a geothermal power plant or the pore space of a rock formation can significantly inhibit fluid production. The goal of our research is to understand the chemical processes that lead to mineral deposition and to develop methods to manage this issue in a working power plant. Our laboratory is equipped to simulate complex processes in geothermal brines in well-defined solutions, whereby the solubility and precipitation rates of various minerals can be studied.

Fluid Physics

Of central importance to the sustainable operation of a geothermal power plant is knowledge of the geothermal fluid's physical properties, such as density, viscosity, ultrasonic velocity, electrical & thermal conductivity and heat capacity. Our laboratory is designed for determining these properties in highly saline fluids at conditions commonly found in geothermal reservoirs. Results from our research are used to expand existing databases for the thermodynamic properties of geothermal fluids.

Physical-Chemical Fluid Monitoring

At the research platform Groß Schönebeck, we operate the fluid-monitoring system "FluMo". The system allows for the determination of relevant physico-chemical parameters in geothermal fluids directly within the geothermal circuit. The system also allows for fluid sampling at various points along the circuit. The FluMo system can support the sustainable operation of a geothermal power plant by monitoring changes in the geothermal fluid's chemistry online and in real-time.

圖 40 GFZ 地質能源研究室熱液特性分析簡介(II)

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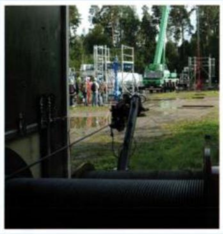
Reservoir Monitoring



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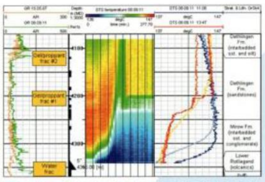
INTERNATIONAL CENTRE FOR GEOTHERMAL RESEARCH

圖 41 GFZ 地質能源研究室儲集層監測簡介(I)

Reservoir Monitoring

We investigate the effects of natural and artificially induced flow processes within the subsurface. Innovative borehole measurement methods are developed and applied within field experiments. The integration with other geophysical and geochemical methods enables a quantitative registration of spatial and temporal changes of subsurface conditions and reservoir properties.
We work on methods which are specially tuned to the requirements of new types of subsurface use, like new ways of extracting geothermal energy (e.g. enhanced geothermal systems, supercritical reservoirs), geological storage (e.g. CO_2, thermal energy), or production of unconventional fossil fuels (e.g. gas hydrates). Moreover novel methods for monitoring of borehole integrity (e.g. cementation) are developed. The measured data enables to derive important information for the safe and efficient use of geological reservoirs.
A special focus is on implementing fibre-optic sensing methods for borehole measurements. Optical fibres are well suited for downhole deployment as they can tolerate harsh environments, i.e. high pressures and temperatures, or strongly corrosive media, and are immune to electromagnetic interference.

GFZ hybrid wireline logging system with fibre-optic sensor cable and electronic downhole tools - pressure, temperature, spinner, gamma ray, casing collar locator (GFZ).



DTS- and production logging data acquired with the hybrid wireline logging system during a production test (GFZ).

Feed-through of a permanently installed downhole sensor cable at the wellhead (GFZ).

Wireline logging

Fluid movement in the subsurface can be quantified by measuring pressure, temperature, as well as flow velocities along a flowing well. A novel hybrid borehole logging system was developed to allow for a combined deployment of fibre-optic and electronic sensors. With our current wireline logging equipment, measurements down to well depths of 6000 m and temperatures of 150 °C can be performed.

Permanently installed sensors

In order to detect dynamic processes within the subsurface and to evaluate the structural wellbore integrity, custom designed cables can be permanently installed along the tubing or behind casing. Together with industry partners, suitable downhole sensing equipment and installation techniques are developed for the deployment in deep wells. Within previous research projects, we have installed permanent sensor cables within wells at depths of up to 1200 m and operating temperatures above 300 °C.

Fibre-optic sensing

Distributed sensing techniques like DTS (distributed temperature sensing) or DAS (distributed acoustic sensing) enable new possibilities for borehole monitoring, as they allow for quasi-continuous acquisition of data over several-km distances with high spatial and temporal resolution. In collaboration with partners from academia and industry we develop novel fibre-optic sensors for measurement of additional physical and chemical parameters in laboratory and field applications.

圖 42 GFZ 地質能源研究室儲集層監測簡介(II)

International Centre for Geothermal Research (ICGR)

The International Centre for Geothermal Research develops scientifically substantiated solutions for a sustainable geothermal energy supply. The research activities are characterized by an interdisciplinary approach, with close synergy of reliable basic and profound engineering research. Particular emphasis is given to the development of Enhanced Geothermal Systems and the sustainable storage of thermal energy in aquifers.
Seven competence clusters at ICGR unite a high level of expertise along the entire chain of geothermal technology. Novel methods and approaches in the fields of geothermal exploration, reservoir engineering and monitoring as well as process and power plant technology cover the relevant processes and interactions underground and above ground.
A key challenge of ICGR's work is the upscaling of research results from laboratory to demonstration scale.
Our in situ Laboratory Groß Schönebeck in the North German Basin allows a fast transfer of new technologies into practical applications.
ICGR maintains global research connections, our scientists are active in many parts of the world. We are leader of European and international research collaborations and a reliable partner for the industry.

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Research platform Groß Schönebeck (from left to right): injection well, experimental hall with corrosion test equipments, cooling towers, power plant moduls, production well (GFZ).

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GFZ

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Reservoir Engineering

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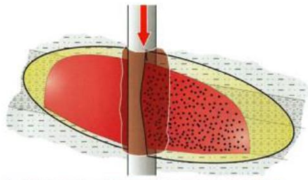
INTERNATIONAL CENTRE FOR GEOTHERMAL RESEARCH

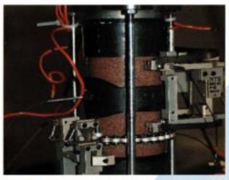
圖 43 GFZ 地質能源研究室儲集層工程簡介(I)

Reservoir Engineering

Reservoir Engineering is essential for an appropriate development of geothermal resources. Optimum economic utilization of geothermal reservoirs requires analysis of the geological system together with adequate planning. These include chemical and petropysical reservoir characterization, reservoir stimulation and modelling as well as understanding of the processes and interaction of the borehole-reservoir system. The control of the amount of fluids produced, well path design, well placement, rate of injection and many other means help to optimize the heat recovery. The reservoir engineer estimates the heat in place, the thermal breakthrough time and optimize the reservoir performance by four major activities: observations, assumptions, calculations (analytical and numerical methods) and development decisions.
The research wells drilled by GFZ at Groß Schönebeck make possible to access and circulate formation fluids in the horizons between 3,9 and 4,4 km at temperatures up to 150 °C. This downhole laboratory provides the opportunity to perform various borehole measurements and in situ experiments, to validate and improve model in use or develop new ones.



Model of vertical fissure produced by hydraulic stimulation (GFZ).



Detail of a mounted specimen assembly (GFZ).

Reservoir model of a geothermal doublet system (GFZ).

Stimulation

Stimulation treatments are an option to enhance the productivity of low permeability geothermal reservoirs by inducing artificial fluid pathways.
At GFZ specific stimulation treatments have been developed to enhance the existing permeability; i. e. hydraulic fracturing, thermally induced fracturing and chemical/ acid stimulation.
In hydraulic stimulation experiments, fluids are injected under high pressure into the subsurface rocks to create new fractures or extend existing fractures.

Rockphysics

Effective energy production from geothermal reservoirs requires that the physical properties of the host rock have to be characterized as precisely as possible. Additionally, rock physical experiments provide a valuable complementary method to investigate particular processes associated with mechanical and thermodynamic changes induced during operation. The results of such investigations improve the outcome of hydro-thermo-mechanical-chemical simulation codes in order to derive statements on reservoir productivity, sustainability, and best-practice operation.

Modelling

An appropriate numerical model is important for planning the well path and fracture design, interpreting hydraulic tests and stimulations, and predicting reservoir behavior during geothermal power production. Such models should include:
(i) the reservoir geology and structure,
(ii) the geometry of wells and fractures and
(iii) the hydraulic, thermal, mechanical and chemical conditions of the reservoir and fractures generated due to changes in reservoir conditions.

圖 44 GFZ 地質能源研究室儲集層工程簡介(II)

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Research platform Groß Schönebeck (from left to right): injection well, experimental hall with corrosion test equipments, cooling towers, power plant moduls, production well (GFZ).

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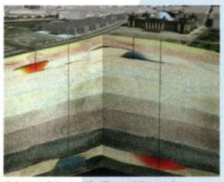
圖 45 GFZ 地質能源研究室電廠規劃興建工程簡介(I)

Process and Plant Technologies

The use of the subsurface for energy production and storage is an important component of future-oriented and sustainable energy supply.
Depending on the temperature of the geothermal resource it is possible to use the heat from the reservoir for direct heat provision, for heat provision on higher or lower ("cold") temperature levels, or for the conversion into electricity. Depending on the fluid flow, geothermal reservoirs can serve for small scale until medium scale energy plants. Although the use of geothermal heat for production or storage of energy is based on the same thermodynamic processes as in conventional energy engineering, most importantly, effects of geological conditions have to be considered and adjusted optimization strategies have to be developed.
The competence cluster "Process and Plant Technologies" is concerned with investigations on energy and process engineering aspects and the optimal coaction of plant components, deep wells and reservoir. The ultimate goal is to improve sustainability and reliability as well as efficiency of the overall system. Besides laboratory experiments and numerical investigations, the realization of pilot projects together with industrial and research partners is an important basis for the research that is carried out. Currently, three pilot sites are being developed and operated, respectively: the In situ laboratory Groß Schönebeck (process engineering & plant technology), the campus of the Technical University of Berlin (investigations on Aquifer Thermal Energy Storage systems), and the geothermal field in Lahendong, Indonesia (demonstration of binary power plant technology).

Well heads of the production and the injection well at the research site in Groß Schönebeck (GFZ).

Installation of the wet cooling tower for the geothermal research power plant in Groß Schönebeck (GFZ).



Scheme of the Aquifer Thermal Energy Storage Systems below the German Parliament Buildings in Berlin (Geothermie Neubrandenburg GmbH & Google Earth).

Process Engineering

The aim in process engineering is reliable production and injection of mineralized and multiphase geothermal fluids. The prerequisite for the reliable setup and operation of a geothermal fluid loop is the selection of suitable components as well as operational parameters. In ongoing research projects, therefore, the response of various materials to corrosive environments as well as scaling processes and degassing are experimentally and numerically investigated.

Plant Technology

The energetic use of geothermal resources requires suitable technical plant concepts that meet the specific site conditions. The investigations at GFZ focus on the optimum integration of binary power plants using geothermal brines with low to medium temperatures at various geothermal sites. Important issues refer to the handling of the geothermal fluid in the plant setup, the removal of the waste heat and the characterization of the operating behavior. Site-specific concepts are developed by means of numerical studies.

Aquifer Thermal Energy Storage (ATES)

Energy supply systems comprising Aquifer Thermal Energy Storages consist of several subsystems: the aquifer, the plant, and the users determining the structure of energy demand. Central aspects in the investigations at the GFZ are the development of numerical models and planning methods which facilitate the engineering of the complete energy supply system and systematic monitoring of operating ATES. Both aspects are elaborated considering the characteristics of all subsystems.

圖 46 GFZ 地質能源研究室電廠規劃興建工程簡介(II)

(2) 印尼 Pangolombian-Lahendong 地熱發電廠設計概述

GFZ 地質能源研究室於 2019 年 1 月交付印尼 Pertamina 石油公司之地熱發電子公司(Pertamina Geothermal Energy, PGE)一座 0.5MW 之 ORC (Organic Rankine Cycle)地熱電廠，該廠位於印尼北蘇拉威西省，GFZ 負責地質探勘、電廠規劃設計施工至運轉測試等工作(圖 47、48)。

該地熱發電廠所在的北蘇拉威西省(圖 49、50)與台灣的大屯山、綠島相同，均屬於安山岩質的島弧火山，地下水成分也較為酸性，因此在進行地熱電廠設計時，為防止熱水與蒸汽造成管線鏽蝕後，必須拆卸整個機組進行維修，故該電廠之設計方式不同於傳統雙循環有機朗肯(ORC)系統，而增加了另一熱交換系統(圖 51、52)。

一般 ORC 地熱發電機組是由圖 51 之紅色、綠色、與藍色三個部分所構成，綠色為發電機組，藍色為冷卻系統，紅色為井場，並直接與綠色部分進行熱交換。若紅色部分管線腐蝕後，含有酸性之流體會進入綠色發電機組部分，造成機組之損壞，因此需要改善設計。

GFZ 於印尼興建之機組多了一個黃色的熱交換系統(圖 51)，該系統將紅色井場部分之熱能交換至綠色發電機組部分，若紅色井場部分之管線腐蝕，造成酸性流體流出，則可直接修復黃色熱交換部分，而不會影響到綠色發電機組部分。此設計為適合於高酸性地下水區域之

ORC 發電裝置，本公司未來可列入考量。

圖 47 Pangolombian-Lahendong 地熱發電廠啟用合照

圖 48 Pangolombian-Lahendong 地熱發電廠設施

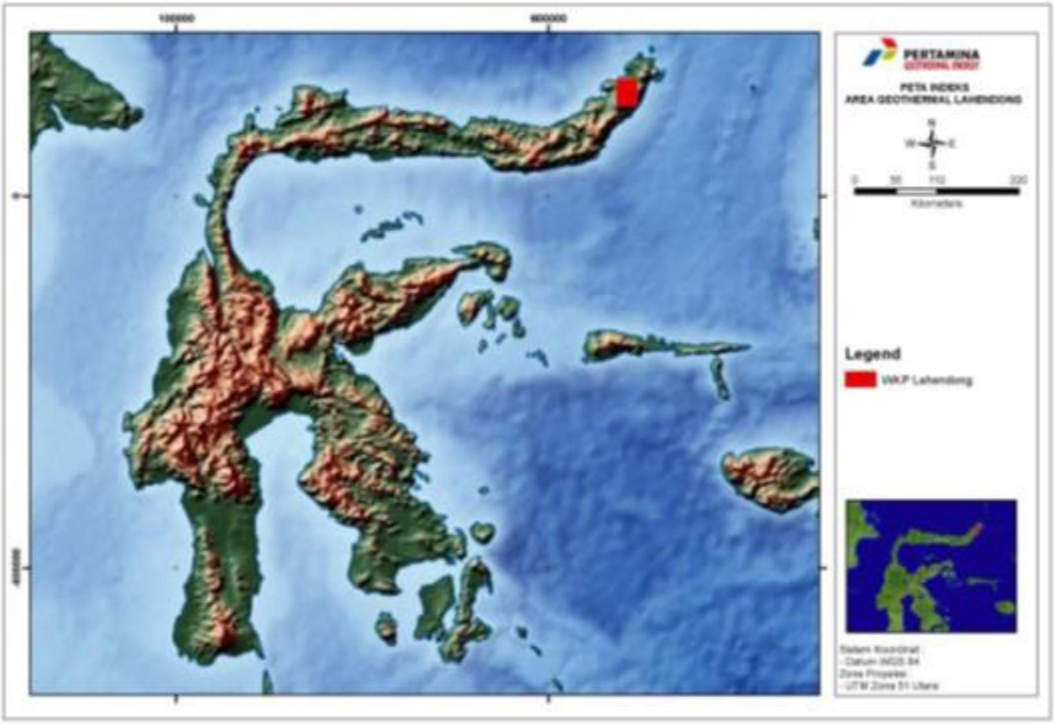


圖 49 Pangolombian-Lahendong 地熱發電廠於北蘇拉威西省之位置

圖 50 Pangolombian-Lahendong 地熱發電廠附近區域地圖

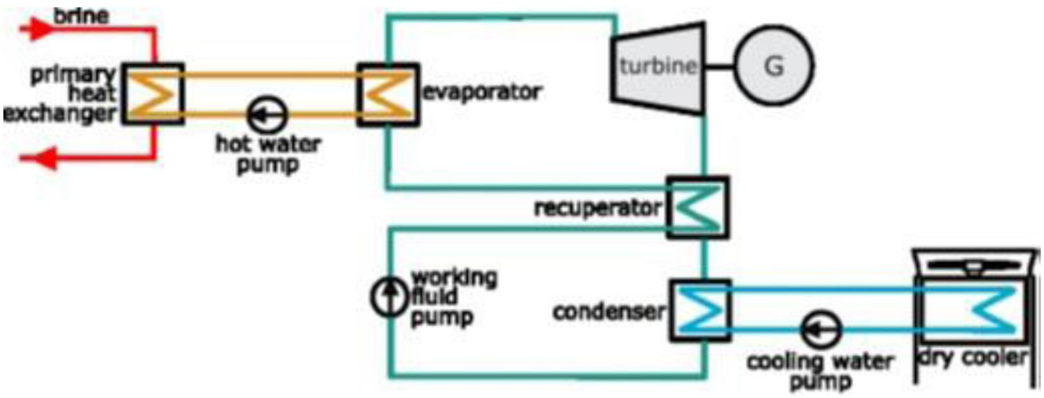


圖 51 Pangolombian-Lahendong 地熱發電廠 ORC 發電機組示意圖

圖 52 地熱電廠設計概念說明海報

(3) 印尼 Pangolombian-Lahendong 地熱區地熱模型建立

自印尼 Pangolombian-Lahendong 地熱區開始進行地熱發電後，管線鏽蝕問題即一直影響電廠之運維，管壁一年可減少 80%，由於生產井之酸鹼值達 2.1，因此過酸之熱液即成為營運電廠的最大挑戰。GFZ 利用地球物理探勘以及熱流模擬，找出附近區域其他可能含有高地溫之區域，之後再進行鑽井取樣，測得熱液酸鹼值為 5.8(圖 53)。該研究室表示，未來將建議印尼地熱開發單位於高酸鹼值區域進行地熱開發，以降低後續營運之成本(圖 54)。

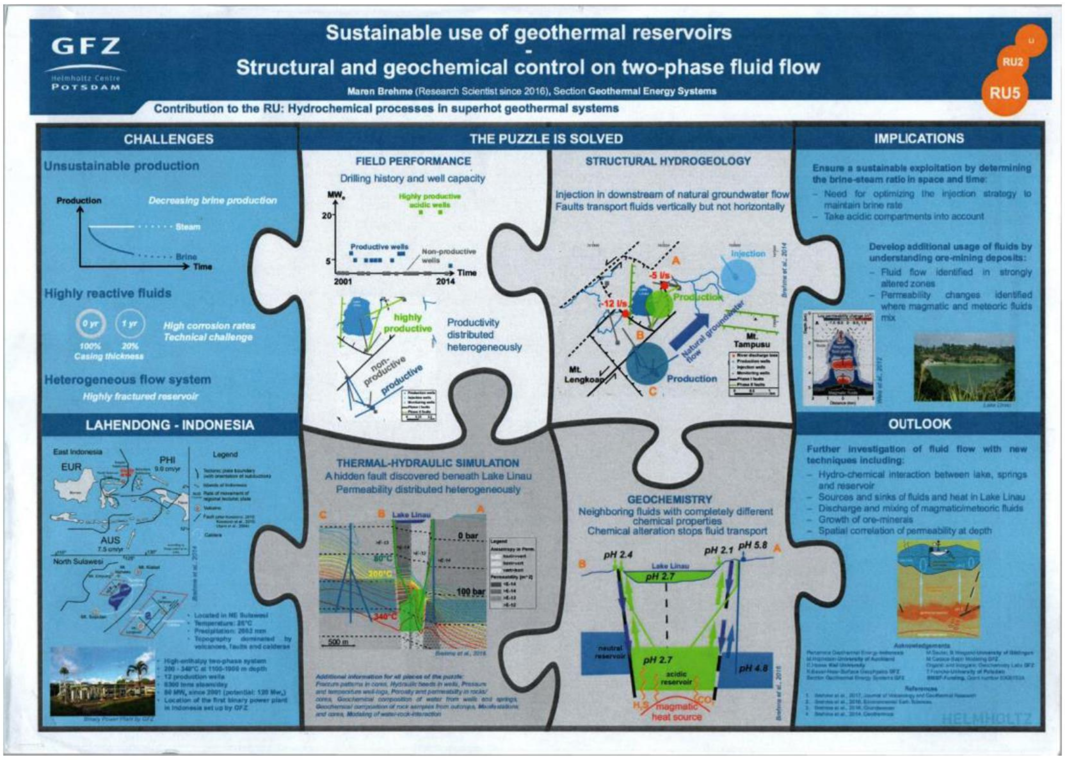


圖 53 印尼 Pangolombian-Lahendong 地熱區地熱模型海報

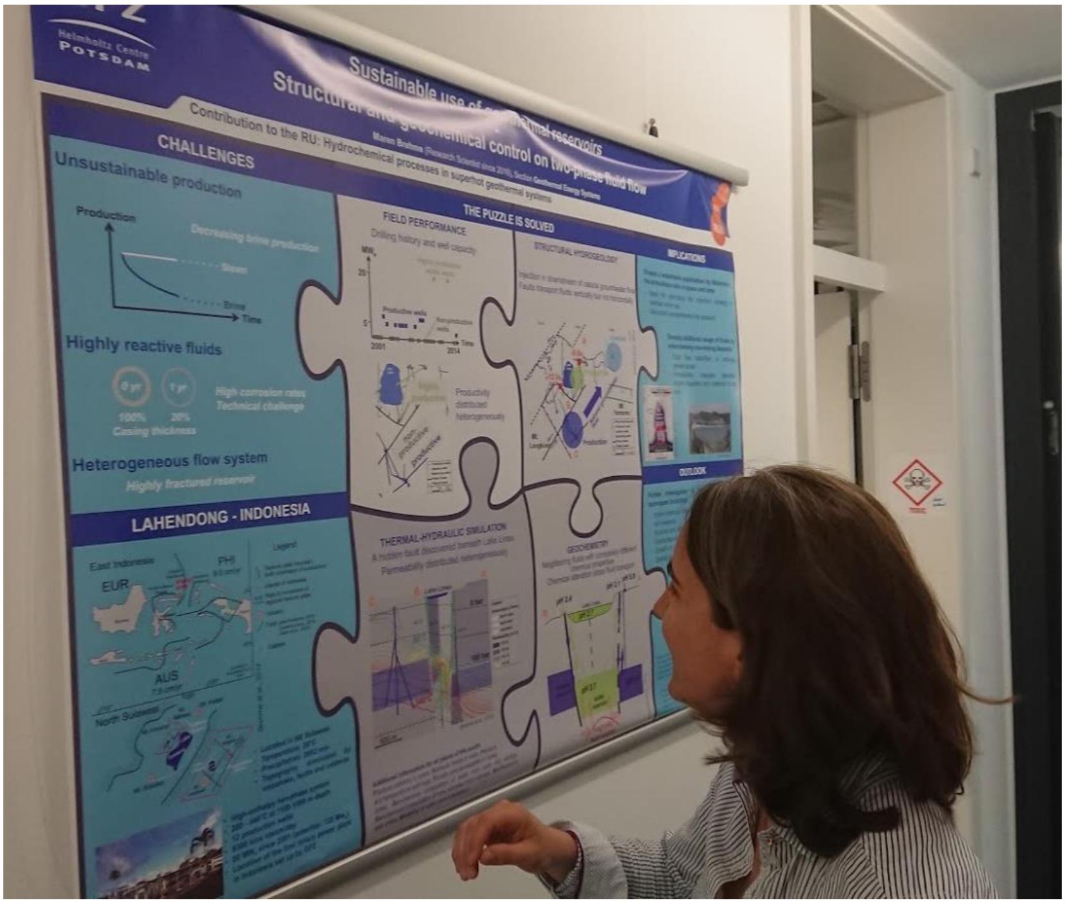


圖 54 GFZ 地質資源研究室 Maren Brehme 博士說明 Pangolombian-Lahendong 地熱區地熱模型海報

(4) 墨西哥 Los Humeros 地熱區探勘技術概述

墨西哥東岸的 Los Humeros 地熱區是該國重要的地熱發電地點，因此當地已有為數眾多之生產井與灌注井。然而，當地的地熱開發商因為有提高發電量的需求，因此仍持續進行新地熱井的鑽探。由於地球物理探勘之金額占據地熱探勘之主要部分，故發展一更低價之地熱探勘技術乃成為墨西哥地熱開發商之主要目標。

GFZ 透過墨西哥聯邦電力監察委員會(Comisión Federal de Electricidad，為墨西哥之國營電力公司)之資金協助，在 Los Humeros 進行土壤逸氣之成份分析。由於地熱活動往往造成藏於地層內的二氧化碳受熱而逸散至地表空氣中，因此 GFZ 即利用土壤二氧化碳通量量測裝置，於地熱區進行高密度之調查，並於調查之後將測得之通量數值透過地理資訊系統(GIS)繪製於電子地形圖上後進行網格外插分析(圖 55)。

研究成果指出，二氧化碳通量的高低與地質構造分布有關，代表此處之地質構造可能同時為高溫流體與二氧化碳之通道。此外該研究團隊亦分析二氧化碳之碳 13 與碳 12 同位素比值的空間分布，得到了碳同位素比值可作為判斷二氧化碳來源是地熱源或是由生物源之依據的結論。未來本公司於安山岩質火山地區進行地熱井選址探勘時，亦可利用此方法協助判斷，減低探勘之風險。

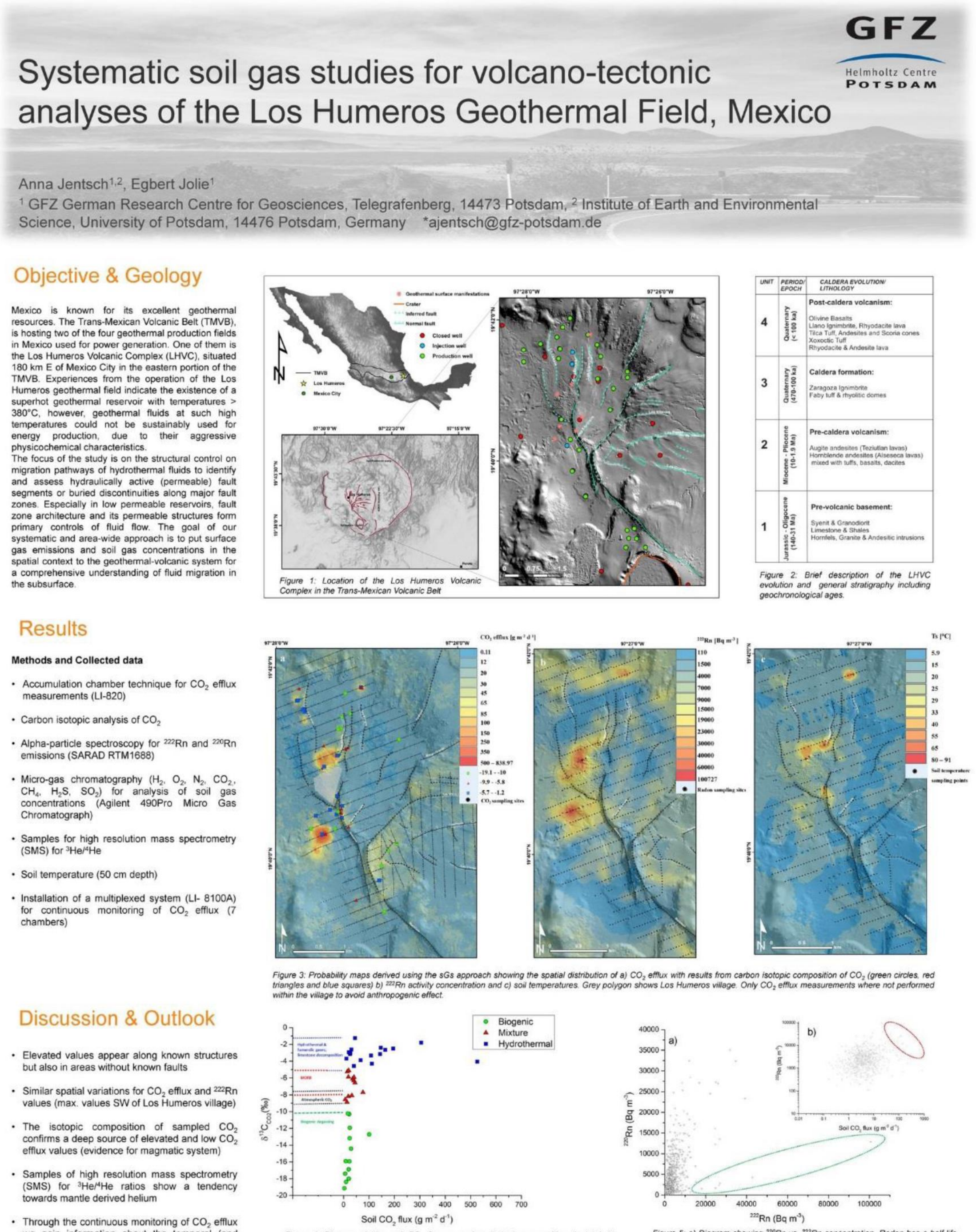


圖 55 墨西哥 Los Humeros 地熱區二氧化碳通量探勘技術簡介海報

第三章　心得及建議事項

本次會議與考察的題目雖看似廣泛，但因為討論議題都圍繞著地質工程領域，故仍有相似之處。雖然行程緊湊，仍經由會議與考察心得提出以下建議事項，作為本公司未來進行碳封存、地熱發電、乃至於地質工程相關業務之參考。

一、 北美地區二氧化碳陸上灌注的監測設備往往都是為了通過環境影響評估而設置，實際上在灌注時並不是所有的感測器都可以監測到灌注二氧化碳引發之變化。

二、 地震的發生仍然是陸上灌注的主要顧慮，加上現在民眾把陸上灌注視為嫌惡設施，因此歐盟開始全力推動離岸灌注計畫。

三、 美國通過 45Q 減稅方案之後，主要企業隨即開始加快 CCS 或 CCU (Carbon Capture and Utilization)的進行，此法案通過可能為川普政府對減碳的少數正面舉動。

四、 由於 45Q 減稅方案鼓勵美國企業進行實質減碳，因此未來美國生產之商品碳足跡可能會降低，進而增加了面對歐洲利用綠電生產之商品之碳足跡競爭力。若未來歐盟開始課徵碳稅，美國企業因已受到 45Q 減稅方案引導而進行 CCS 或 CCU 之緣故，可能不會造成太大之損失。相對於歐盟與美國，我國至目前為

止仍未針對企業主動減碳實施獎勵措施，未來可能造成商品碳足跡無法下降而難以打入歐美市場之後果，因此本公司應持續注意國外減碳政策之發展，並加快實質減碳之步調。

五、 2018 北海道地震並無引發苫小牧灌注場的井下變化，而該區二氧化碳灌注亦無引起有感地震，因此可證明小規模二氧化碳灌注在西太平洋地震帶國家進行的確可行，且不會造成相關之地震災害。未來本公司可利用該案例做為民眾溝通內容，以加速二氧化碳地質封存業務之進行。

六、 GFZ 的地質能源研究室在地熱發電上有相當程度的能力，不但有地質探勘、建廠、乃至於後續運維都有實績，未來本公司或可考慮與 GFZ 交流地熱發電相關事宜。

七、 地熱能源開發從探勘、可行性評估、設計、建廠、以及營運階段都需要數十位地質師、地球物理師與儲集層工程師之合作參與，未來建議本公司可利用國營事業招考之地質、地球物理、以及石油開採三個考科進用相關人員。

八、 由於台灣目前地熱探勘之人才缺乏，僅有少數大學訓練相關人力，未來本公司若規劃長遠之地熱發電計畫，則建議以獎學金方式栽培人才，達到永續經營之目的。

九、 目前本公司地熱探勘之相關軟硬體數量尚待加強，地質與地球物理人力也分散於各事業部體系之中，以至無法將地熱探勘相關核心技術進行最佳化發展。若要達到 2025 能源配比目標之地熱發電裝置容量，則建議將公司內部相關人力整合至一任務編組單位，進行地質探勘、電廠可行性研究規劃、環境影響評估、以及建廠等相關作業。俟電廠完工之後，以新進人員搭配再生能源處之同仁做為地熱電廠營運主力，同時將前期協助地質探勘之其他單位人員歸建至原本單位，以達到人力運用最佳化之目的。

十、 由於台灣東部花東縱谷為台灣主要地熱能蘊藏區之一，而花東地區發電量亦少於該區之用電量，因此建議未來本公司可進行花東縱谷之地熱能開發，平衡該區域之電力供需。