The Jizan Carbon Mineralization Pilot:
Lessons Learned from Lab to Field

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NIM Industry Insights Series - Beyond Capture: CO_2 Mineralisation and Carbon Recycling for a Net-Zero Industry

April 21, 2026

جامعة الملك عبدالله للعلوم والتقنية

King Abdullah University of Science and Technology

Outline

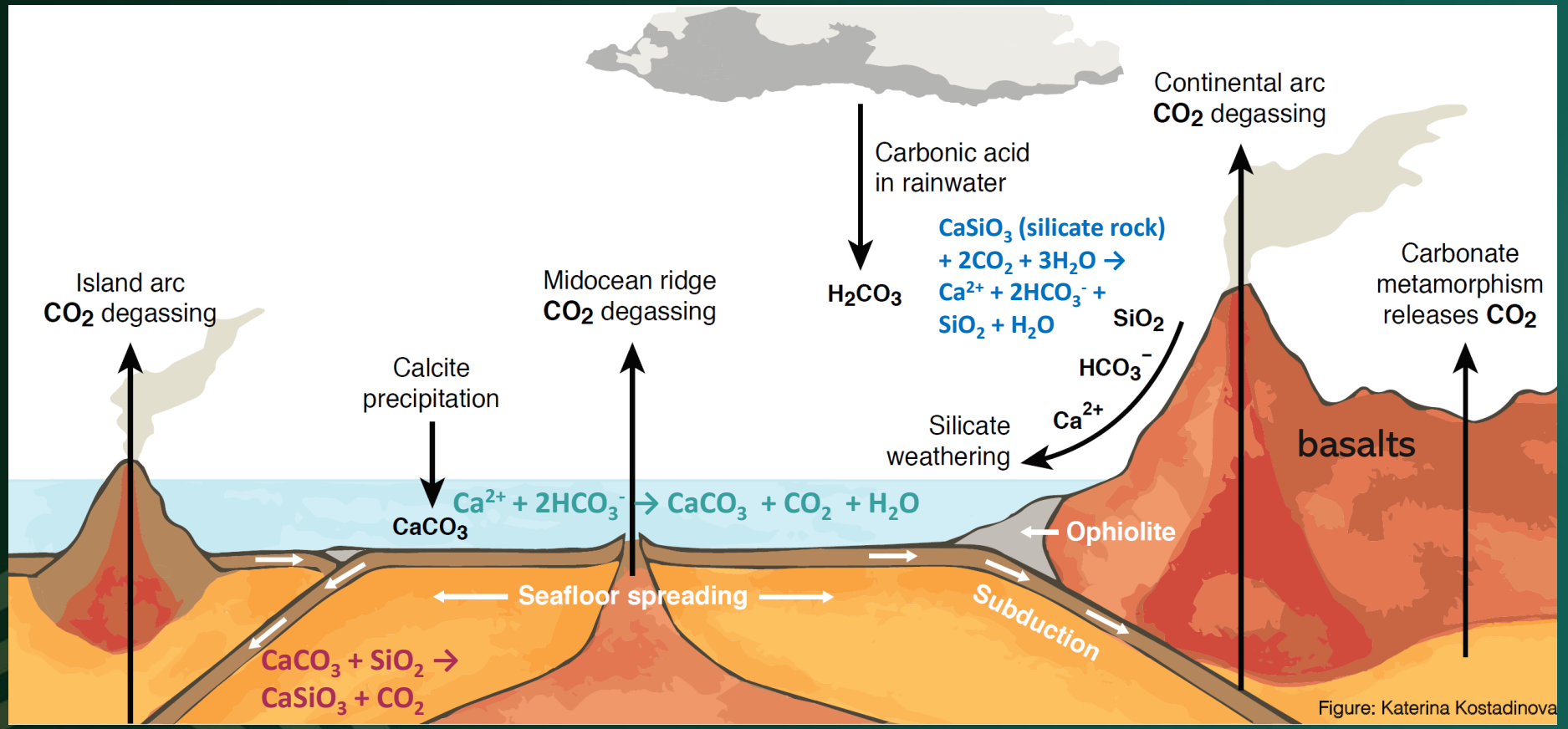
- Background

  Jizan Pilot Deployment :

- Field Assessment
- Lab Investigation and Modeling
- Pilot Design & Execution
- Key Results

Inorganic Geological Carbon Cycle

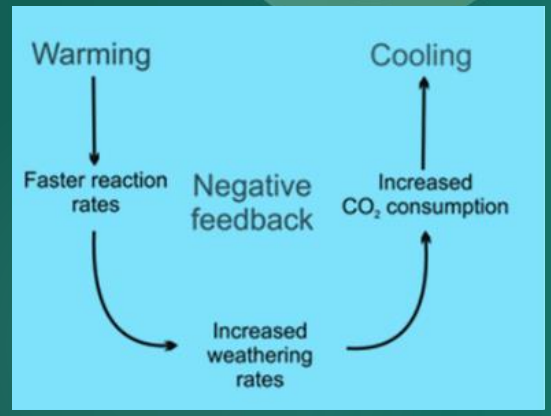
Carbonate-silicate cycle

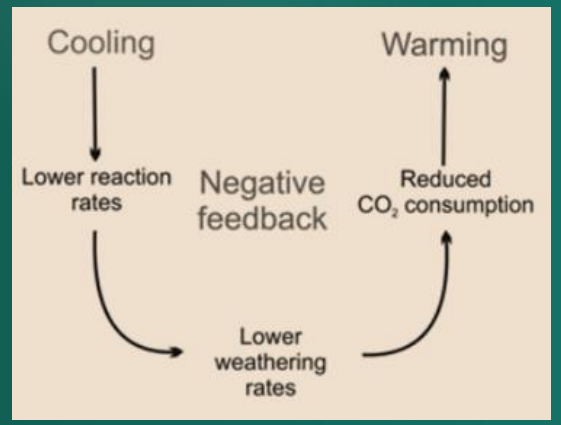


https://cce.nasa.gov/ocean_biology_biogeochemistry/ocean_worlds/about.html

Kasting, 2019

Earth's Thermostat





Walker, Hays, Kasting, 1981

CO_2 Mineralization in Carbonate Minerals

CARBON DIOXIDE DISPOSAL IN CARBONATE MINERALS†

KLAUS S. LACKNER‡,§ & CHRISTOPHER H. WENDT¶
DARRYL P. BUTT‡, EDWARD L. JOYCE, JR.‡ & DAVID H. SHARP‡

‡LOS ALAMOS NATIONAL LABORATORY

1995

Proposed "*a safe and permanent method for CO_2 disposal based on combining CO_2 chemically with abundant raw materials for stable carbonate minerals (calcium and magnesium carbonates)*"

Two approaches to the carbonation of calcium and magnesium oxides :

1- Direct carbonation at high temperature
2- Carbonation in the aqueous phase (low temperature)

Rock		MgO, wt%	CaO, wt%	R_C	R_{CO_2}
Peridotites	Dunite	49.5	0.3	6.8	1.8
	Harzburgite	45.4	0.7	7.3	2.0
	Lherzolite	28.1	7.3	10.1	2.7
Serpentinite		~40	~0	~8.4	~2.3
Gabbro		~10	~13	~17	~4.7
Basalt	Continental tholeiite	6.2	9.4	26	7.1

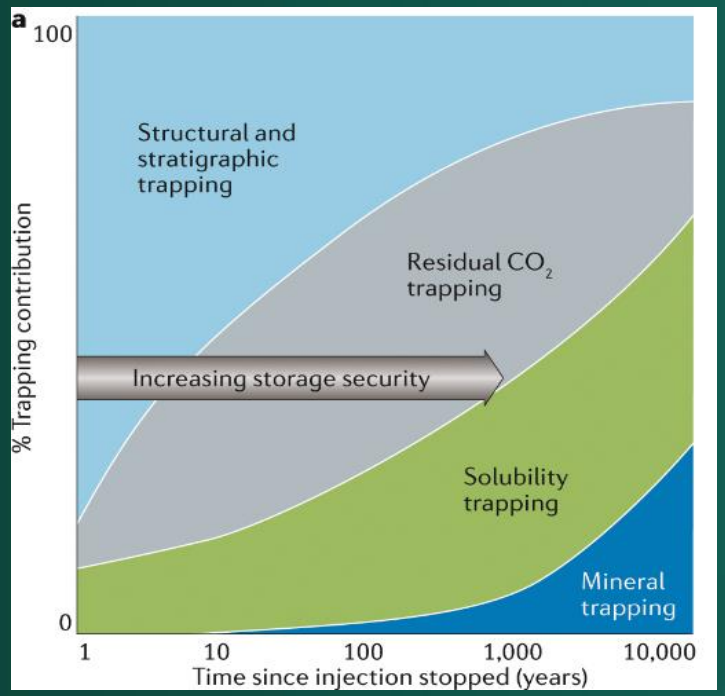
Lackner et al. 1995

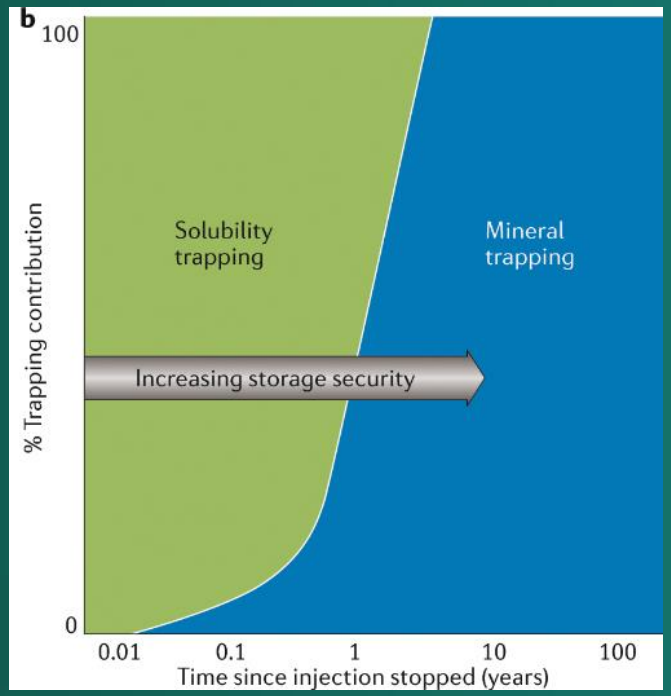
CO_2 Mineralization in Basalts

- Dark-colored, fine-grained, igneous rock
- Porous, but generally has **poor permeability**
- Mainly composed of **plagioclase** and **pyroxene**
- **Rich in divalent cations** such as Ca^{2+} and Mg^{2+} that react with CO_2 to form stable carbonate minerals e.g. calcite, magnesite

Pilots (>100 tons):

- ✓ Wallula Washington, USA (2013)
- ✓ Carbfix, Iceland (2012)
- ✓ Jizan, KSA (2023-2024)

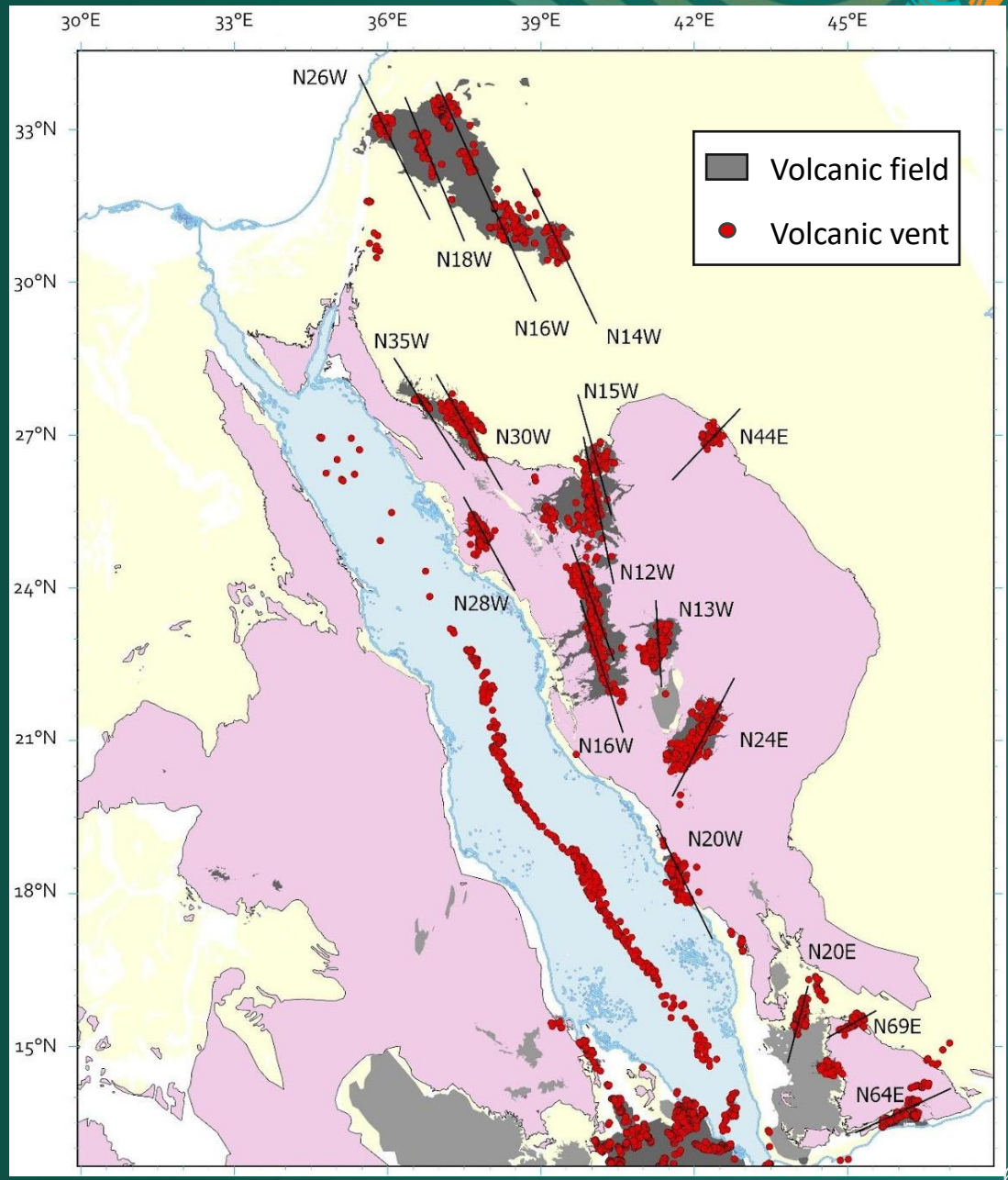




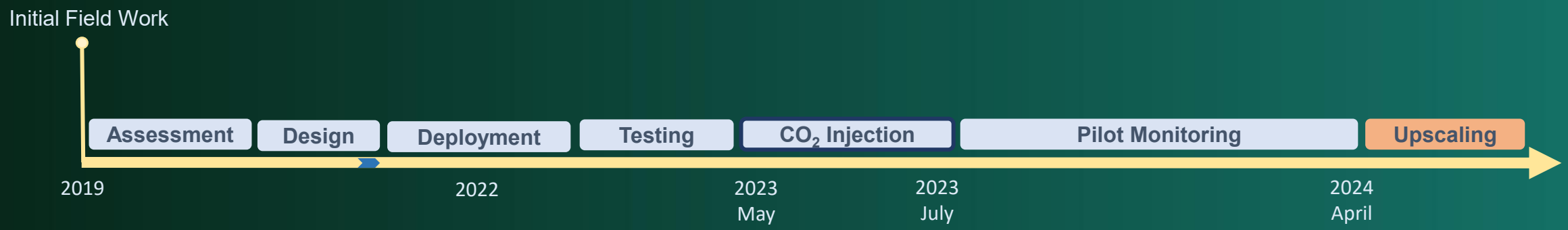
(Snæbjörnsdóttir et al., 2020)

Basalts in Saudi Arabia

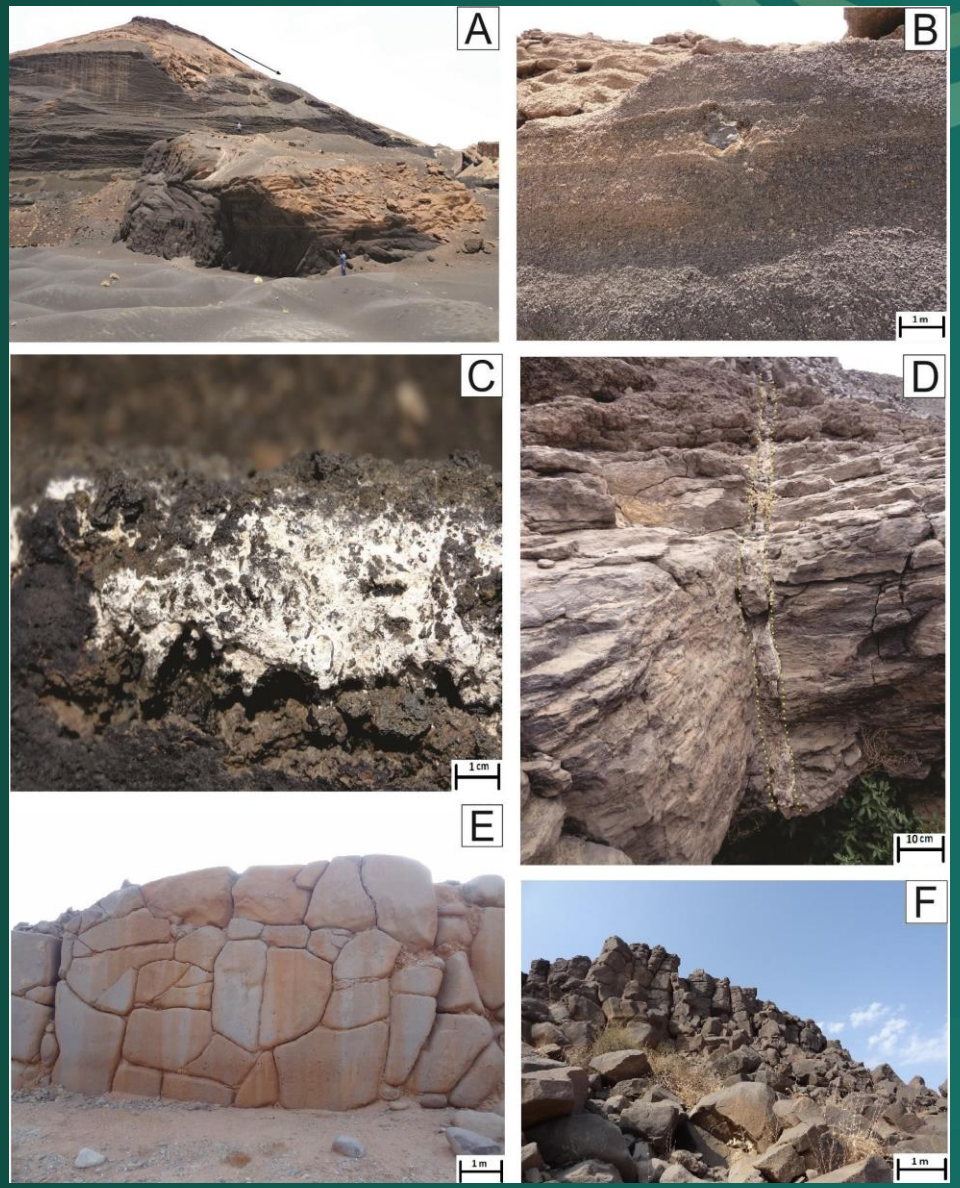
- Saudi Arabia is rich in volcanic (Harrat) and mafic formation in the western region
- Basalt and other reactive formations have the potential to remove CO_2 permanently



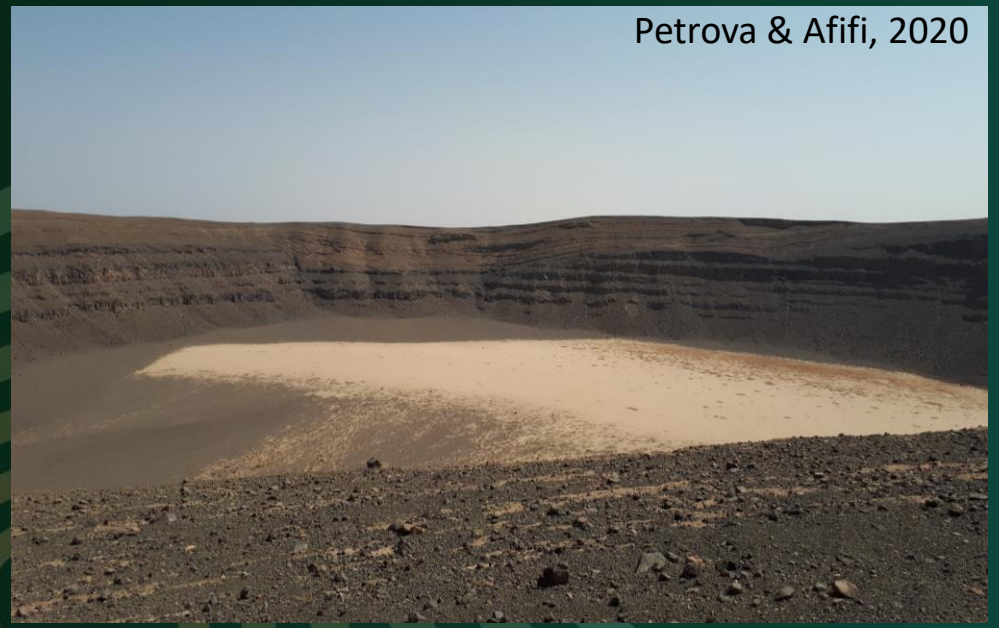
Jizan CO_2 Mineralization Pilot



Field Assessment (Resources)

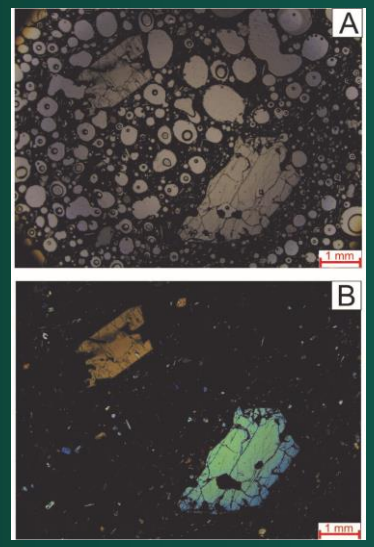


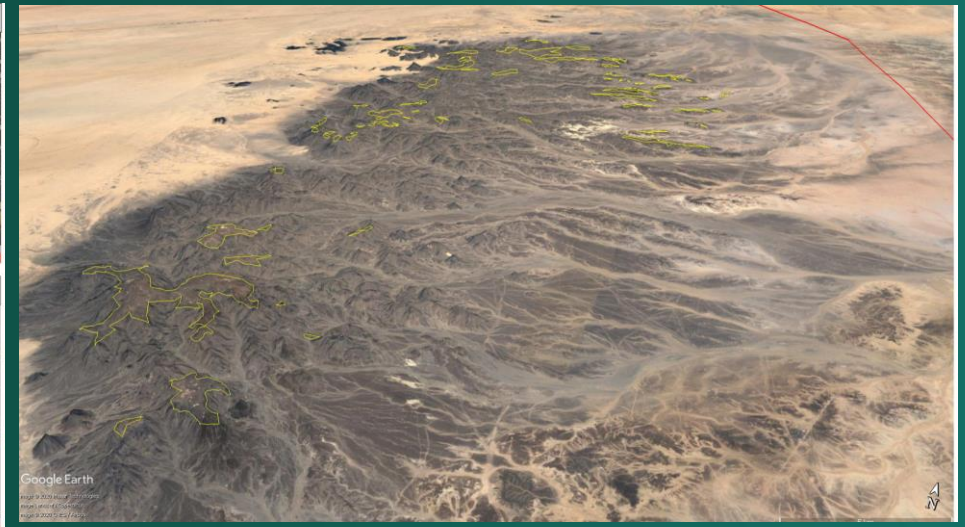
Basalt Characterization (suitability)



Name of the rock	Volume % in rock	Plagioclase composition % anorthite	Volume fraction of anorthite	Weight mineral kg/m^3	Weight fraction Ca in mineral	Ca in mineral kg/m^3	Kilomoles Ca/m^3 rock
31A altered basalt **plagioclase**	15	30	0.045	123.75	0.25	31.17	0.78
33A fresh porous unaltered basalt plagioclase	10	62	0.062	170.50	0.25	42.95	1.07
Name of the rock	**Volume % in rock**	**Pyroxene composition % diopside**	**Volume fraction of diopside**	**Wt mineral in kg/m^3**	**Weight fraction Ca in mineral**	**Ca in mineral kg/m^3**	**Kilomoles Ca/m^3 rock**
31A altered basalt **clinopyroxene**	5	85	0.043	144.50	0.19	26.75	0.95

Table 5.1: Calcium content in plagioclase and pyroxene from Harrat Rahat

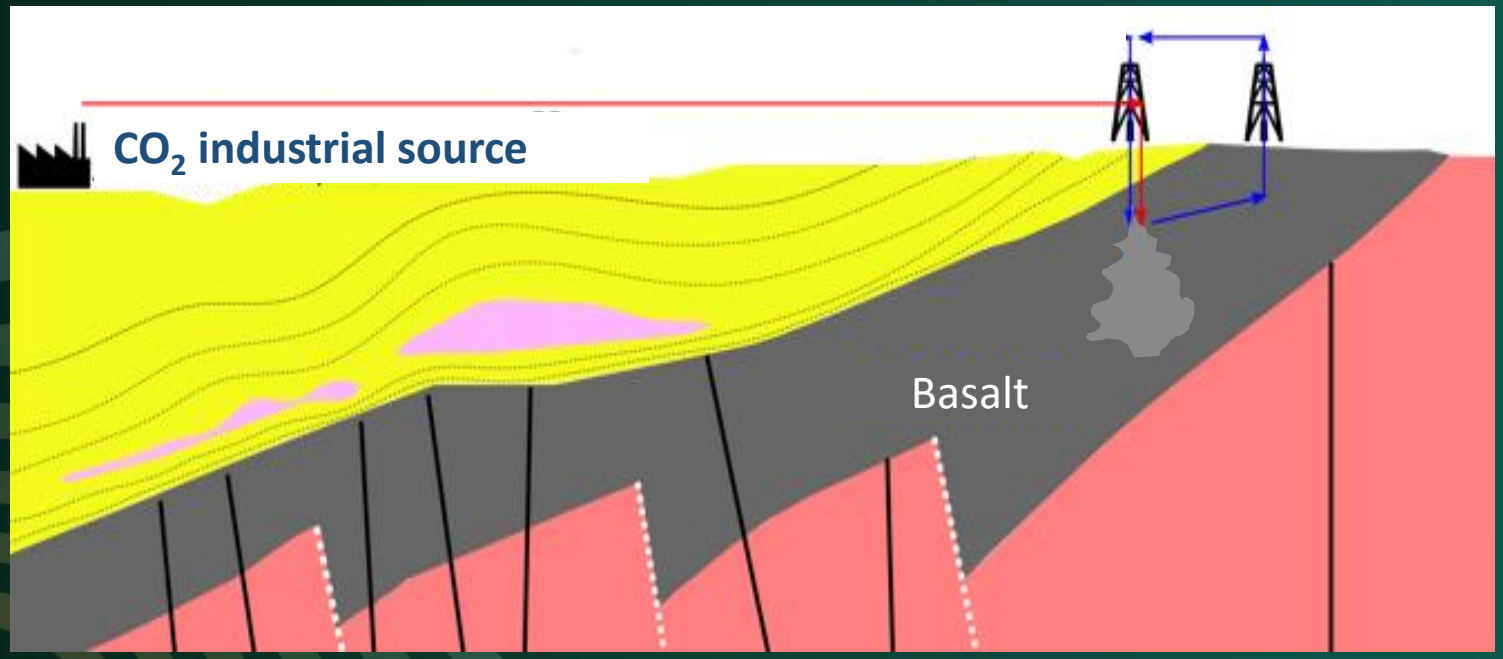




Pilot Selection in Jizan

The Jizan basalt is well suited for carbon mineralization :

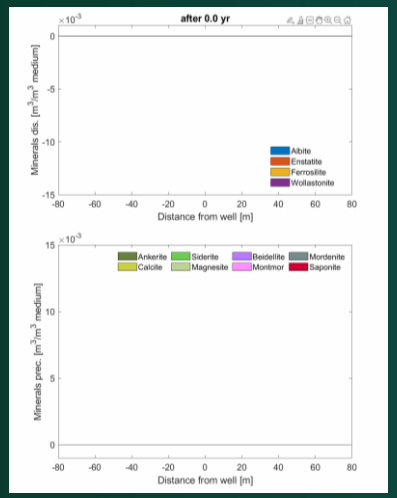
- Geologic setting is favorable and well known
- Contain large volume of basalt at various depths
- Close to sources of CO_2 and SO_2 in Jizan Economic City
- Seawater is available for injecting CO_2 into the basalt reservoir

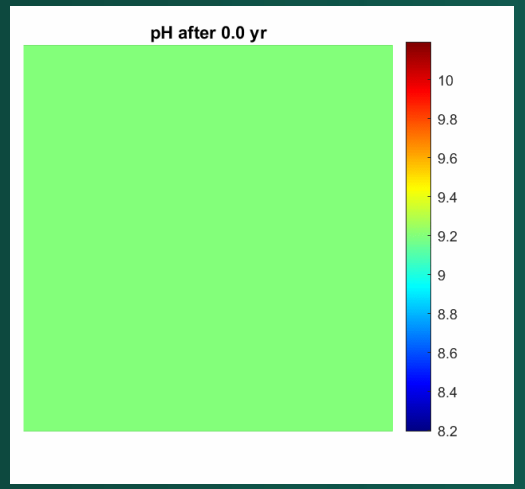


Oelkers, Hoteit et al. 2022, The subsurface carbonation potential of basaltic rocks from the Jizan region of Southwest Saudi Arabia, J. GhGC

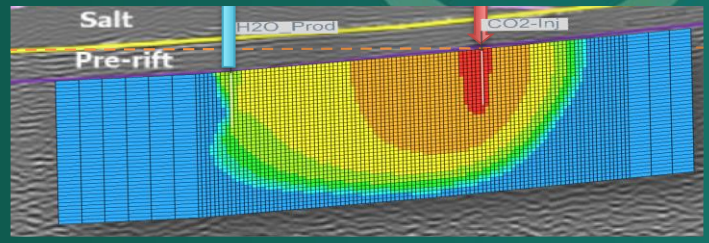
Pilot Design: Lab and Modeling Studies

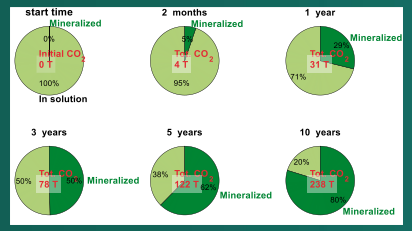
Lab-scale modeling

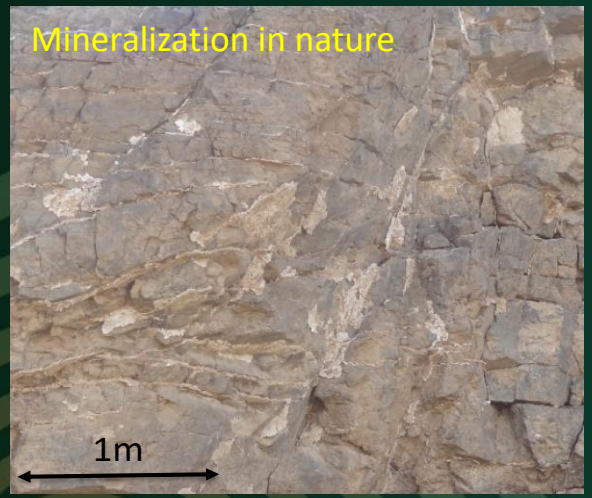


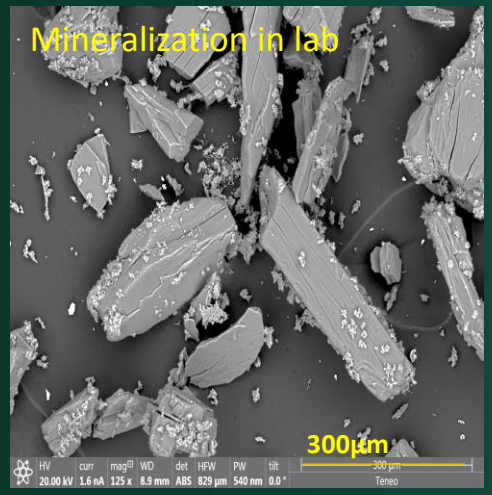


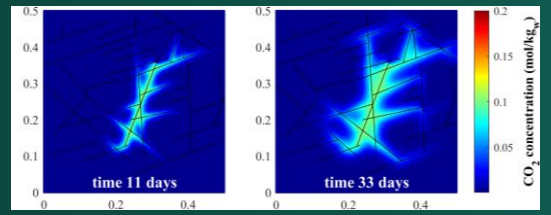
Field-scale modeling

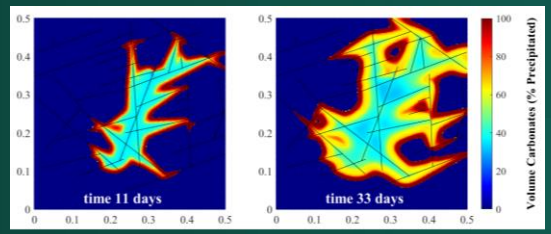


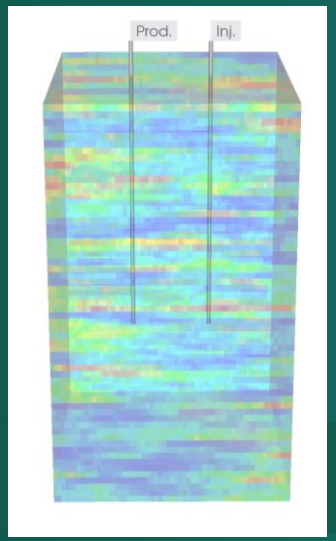


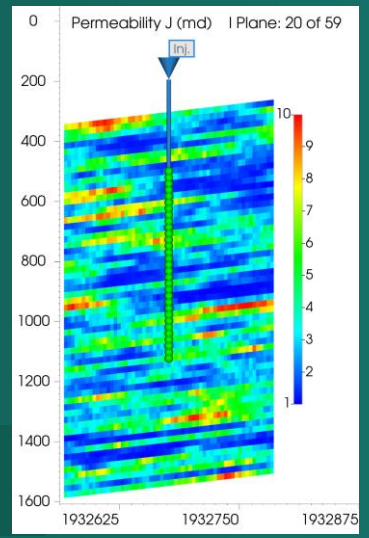










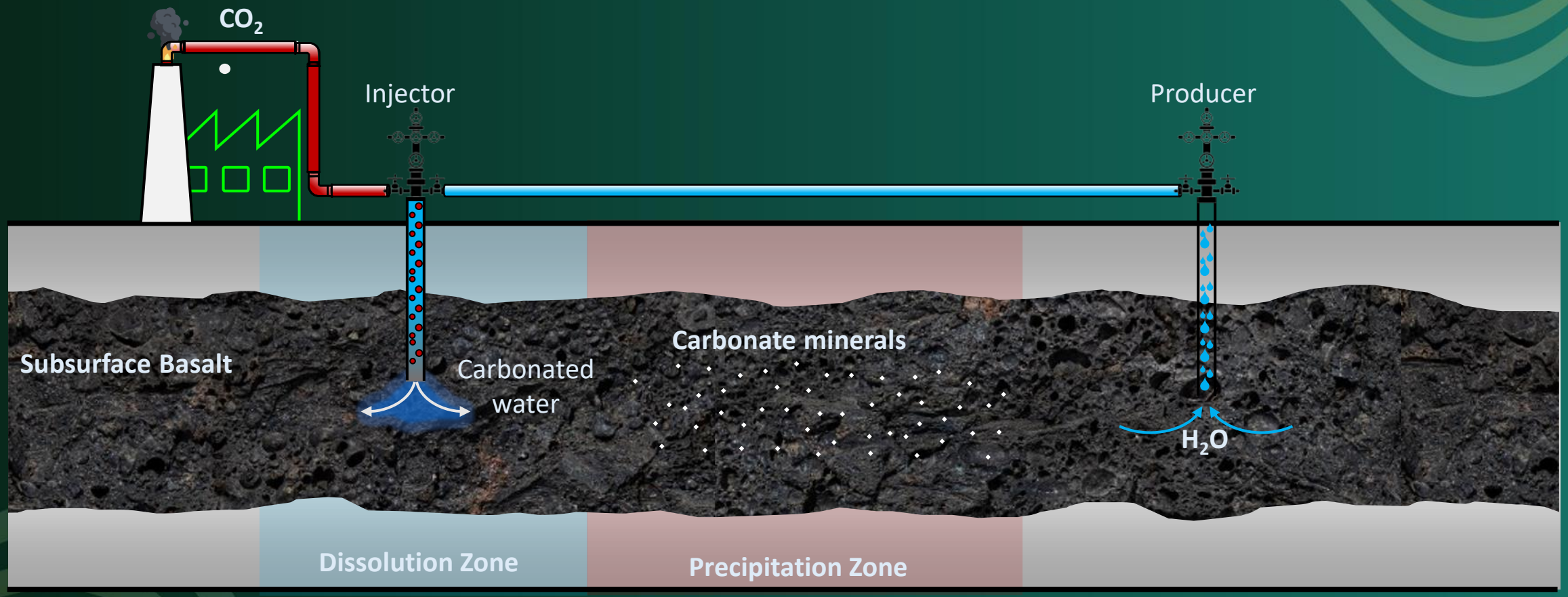


Omar, Addassi, Berno,…, Oelkers, Hoteit(2025). An experimental study of the mineral carbonation potential of the Jizan Group basalts. *J of Greenhouse Gas Control*

Alqahtani, Addassi, Hoteit, & Oelkers (2025). Rapid CO2 mineralization by zeolite via cation exchange. *Scientific Reports*

Addassi, Hoteit, & Oelkers (2024). The impact of secondary silicate mineral precipitation kinetics on CO2 mineral storage. *J. of Greenhouse Gas Control*,

Closed-Loop System



CO_2 Dissolution in Water: $CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + H^+$

Basalt Dissolution: $CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Ca^{2+} + 2HCO_3^- + Al_2Si_2O_5(OH)_4$

Carbonate Precipitation: $Ca^{2+} + CO_3^- \rightarrow CaCO_3$ (Calcite)

Animation courtesy of Abdulwahab Alqahtani

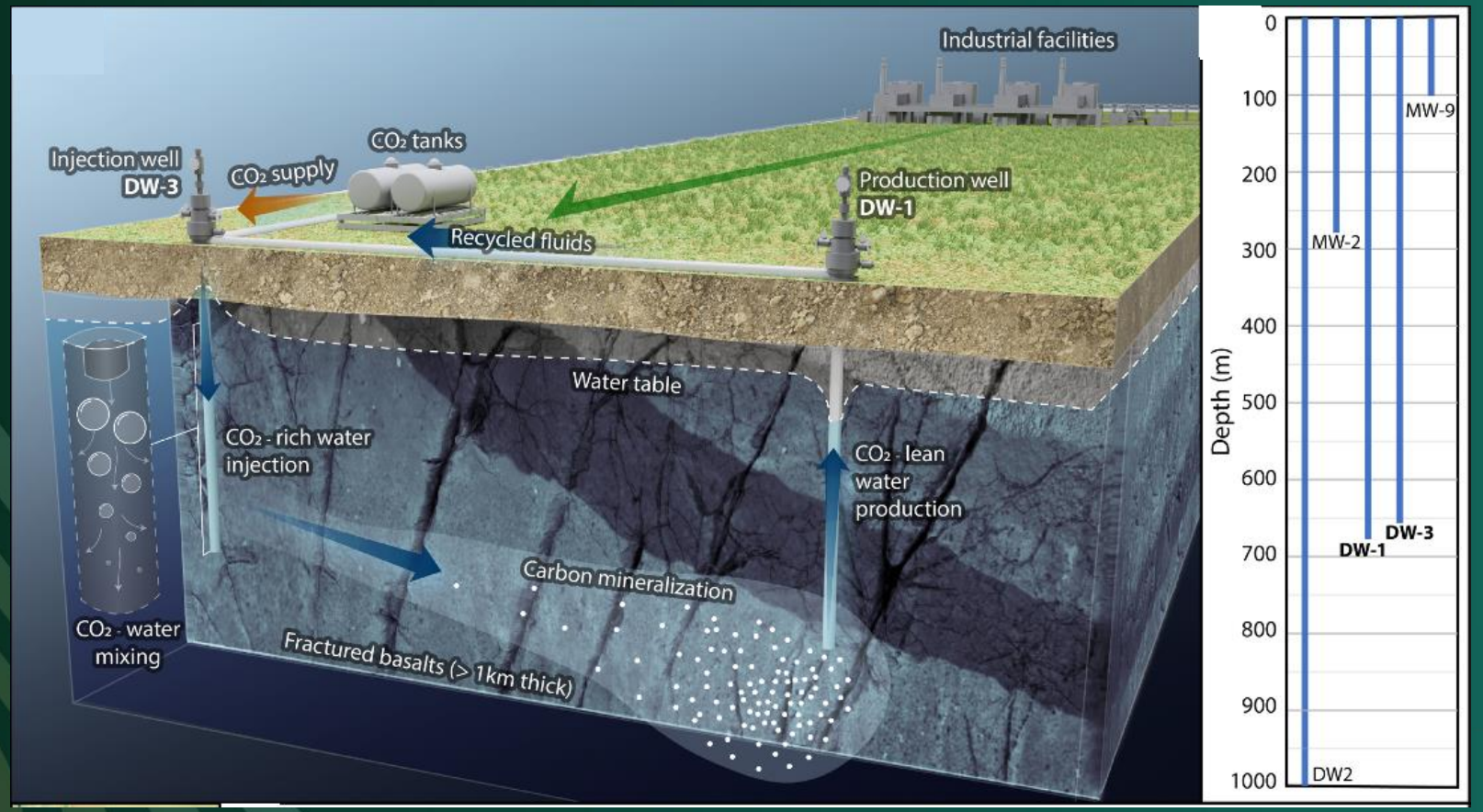
Jizan CO_2 Mineralization Pilot

Initial Field Work — Drilling — Circulation — Tracer Testing (NaF)

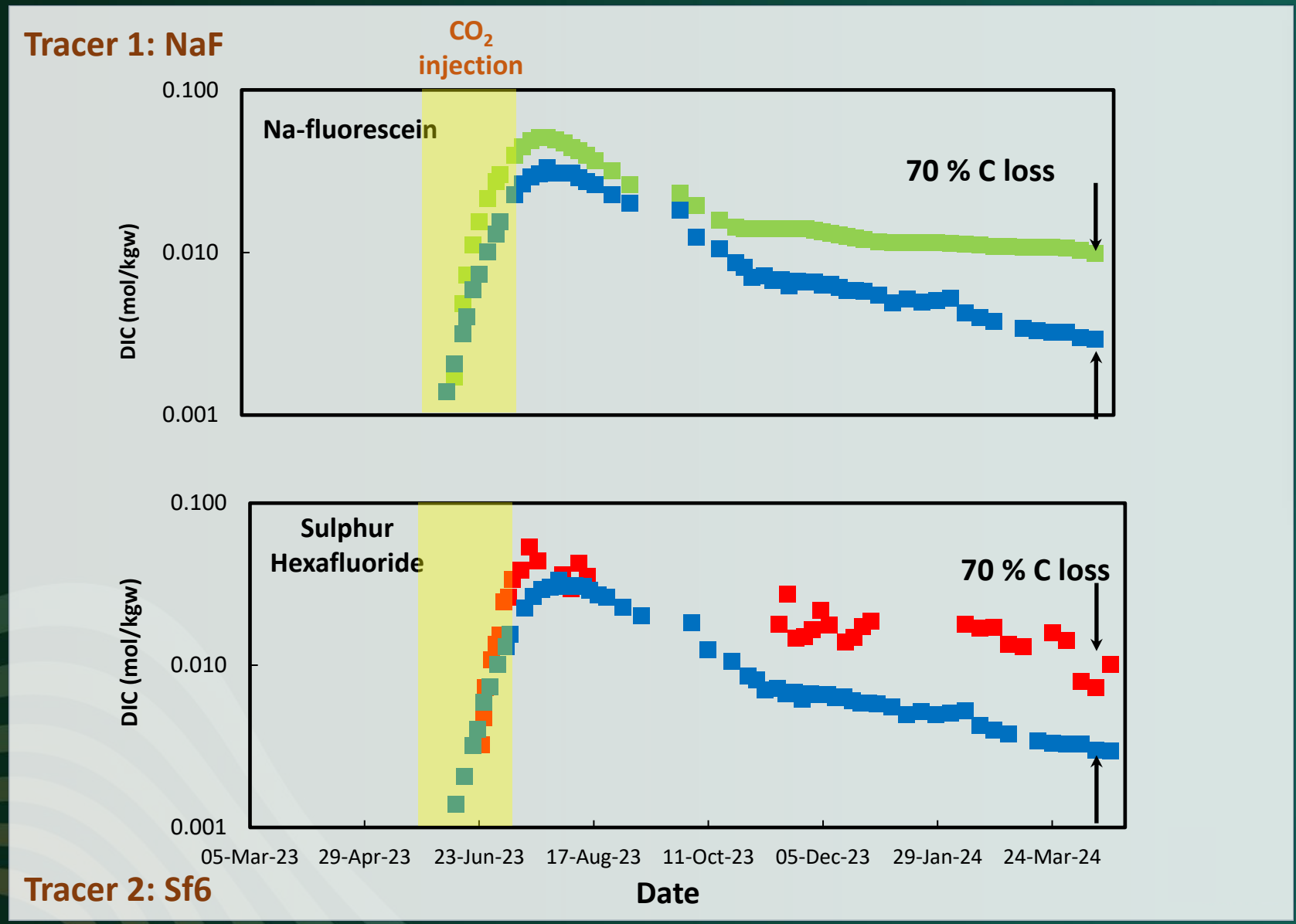
~130 tons

Preparation Stage	Pilot Testing	CO_2 Injection	Pilot Monitoring

2019 — 2022 — 2023 March — 2023 April — 2023 May — 2023 July — 2024 April



Quantification of CO_2 Mineralization : 70% within 10 months



Take Away

- Two-well system (130 m apart, drilled to ~1000 m)
- Full formation (brackish) water recirculation, no external water required: critical for water-scarce arid regions)
- Location adjacent to major point-source carbon emitters in Jizan, KSA.

- Fractured basalts (Jizan Group, 20-30Ma) at ~ 45°C, target depth >350 m, ~hydrostatic pressure conditions.
- Pre-injection of tracer (sodium fluorescein) revealed a dual-permeability flow system consisting of few large fractures + extensive smaller fractures (matrix)
- Effective pore volume (PV) estimated at 24,000–43,000 m^3
- 10% PV in fast flow in fracture (50–65-day residence time) + 90% PV in low-permeability matrix (255–445 day residence time)

- CO_2 dissolved directly into recycled formation water within the wellbore at 150 m depth (12–14 bar delivery pressure)
- 131 tonnes of CO2 injected over ~37 days at a CO_2:water-mass-ratio of 1:65 (not optimized, below solubility at reservoir conditions).
- SF6 co-injected with CO2 as a conservative tracer.

- About **70%** of injected CO_2 mineralized within ~10 months
- Dominant phases: calcite, ankerite, and siderite

Note: Carbon Mineralization is not a replacement for conventional CCS, it is strictly complementary; geological setting /conditions dictates applicability

Collaborators on Jizan Pilot:
Eric H. Oelkers, Serguey Arkadakskiy, Zeyad Ahmed, Noushad Kunnummal, Jakub Fedorik, Massimo Marchesi, Mouadh Addassi, Abdirizak Omar, Niccolo Menegoni, Sigurdur R. Gislason, Grimur Bjornsson, Davide Berno, Thomas Finkbeiner, Abdulkader Afifi, Hussein Hoteit

CO_2 subsurface mineral storage by its co-injection with recirculating water. ***Nature* 651**, 954–958 (2026). https://doi.org/10.1038/s41586-026-10130-5

Pilot site: Part of the Team