Understanding Deep Sea mineralization: A *sustainable* path forward with CO_2

Basalt-seawater-CO_2 interaction simulating Artic Mid-Ocean Ridge (AMOR) environment. The mineral trapping of CO_2 and the mineral resources formation at Deep Sea: An experimental study

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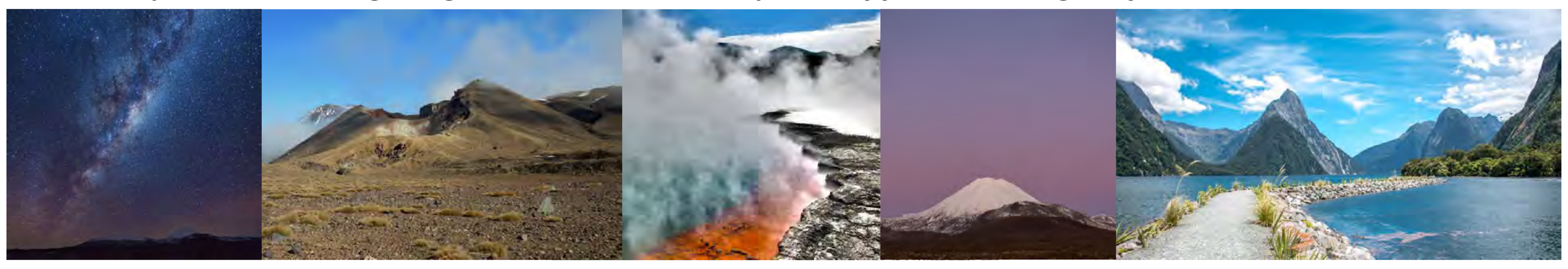
Background and Motivation

I am a Geologist, with a Ph.D. in Hydrothermal Geochemistry carried out at GNS Science, New Zealand, within the "*Geothermal: The Next Generation*" Programme (some pictures of New Zealand landscapes just below and here). My personal background in aqueous geochemistry is strongly focused on the experimental simulations of rock-fluid-CO_2 interaction at subcritical and supercritical condition for both offshore and onshore environments. The experimental approach is for me the foremost alternative to directly duplicating these geological settings, and it represents the closest that I can get to *actually observing* the real environment. Joining the SEAS programme at UiB offered me the great opportunity to continue my experimental studies aimed at the better understanding of some of the mechanisms regulating these geological settings.

I aim to provide reliable geological data to the development of facilities designed for decarbonization.



Current Academic Project

My current research focuses on the experimental simulations of basalt-seawater-CO_2 interaction for the study of mechanisms regulating the mineral trapping of CO_2 and the formation of mineral deposits on the seabed. The work is conducted by combining laboratory facilities at the Centre for Deep Sea Research and Equinor ASA.

Main Questions and Research Plan

Generally, we must rely on computational and experimental approaches to investigate the processes that occur when fluids interreact with rock materials at temperatures and pressures found on and below the seabed. Current computer software packages (e.g., PHREEQC, MINTEQ, Geochemist's Workbench®, TOUGHREACT) can be used to model these environments utilising thermodynamic data which are relatively well-known, at least up to 300˚C. At present, however, in sub-seafloor environments, physicochemical conditions often exceed this temperature and computer modelling is more problematic due to a lack of appropriate thermodynamic data. The experimental approach offers *the only* alternative to directly replicate the basalt-seawater-CO_2 interaction that occurs in submarine hydrothermal systems. Such studies are challenging due to many technical and physical parameters involved, including the sophisticated equipment required. However, the information derived is of great value.

(a) Complete view of the hydrothermal reactor system in flow-through at Centre for Deep Sea Research; **(b)** close view of the furnace, and pressure vessel (51 cm height) containing the basaltic rock; **(c-d)** oceanic pillow basalt with basaltic glass; **(e)** basaltic glass grains (63 – 125 μm).

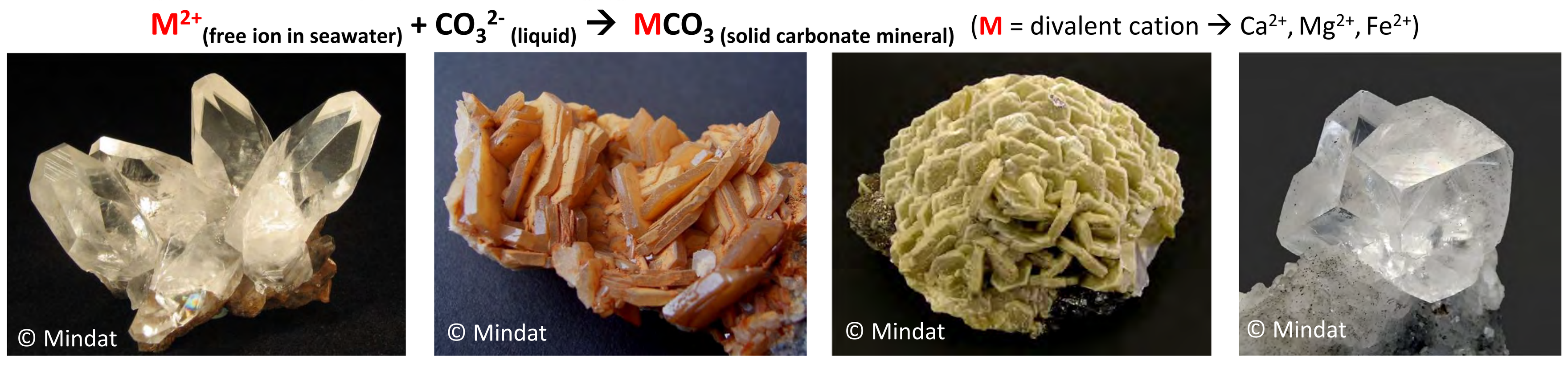
Advanced methods of laboratory experiments of fluid-rock-gas interaction can contribute vital information to the understanding of important geological situations occurring in sub-seafloor hydrothermal systems. An important aim will be to thermodynamically inter-relate the evolved reacted experimental fluid chemistry with the observed hydrothermally-produced secondary mineralogy. In previous experimental studies (mostly carried out in batch reactor systems), some insight was gained into the basalt-seawater-CO_2 exchanges that gave rise to the fluid chemical signature; however, several fundamental questions remain. The results of my experimental research will give access to further knowledge of several ocean floor processes occurring at AMOR (and onshore environments), including:

- the effect of basalt-seawater-CO_2 interaction on the fluid chemical evolution, mineral solubilities, secondary mineral formation, and permeability at several hydrothermal conditions;
- the mass transport across lithological boundaries in the subseafloor due to reaction with hydrothermal fluids;
- the time scale of chemical alteration in mafic system (i.e., kinetics of reactions).

The laboratory experiments will enhance the evaluation of deep geological resources in terms of:

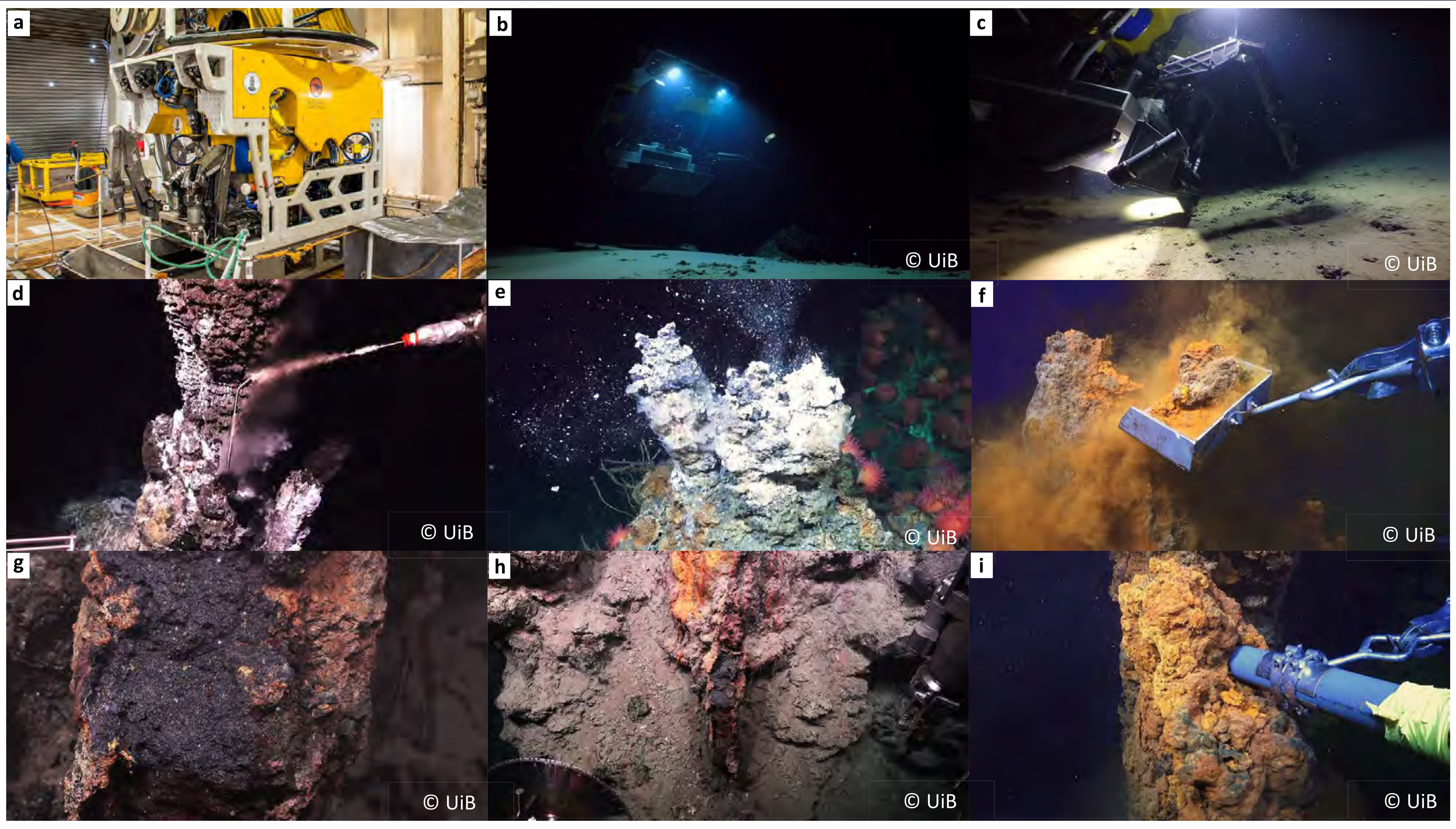
1. **Carbon Capture Utilities Storage (CCUS).** Demonstration and quantification of the potential mineral trapping of CO_2 in basalt through the formation of secondary carbonate minerals in the Deep Sea. Elements such as Ca^{2+}, Mg^{2+} and Fe^{2+} (already present in seawater as free ions and of derivation from the hydrothermal alteration of oxide minerals in basalt) in contact with liquid CO_2, and at relative basic/neutral pH of solution, form stable carbonate minerals (pictures below) by the following (geochemical) reaction:

$$M^{2+}_{\text{(free ion in seawater)}} + CO_3^{2-}{}_{\text{(liquid)}} \rightarrow MCO_{3\,\text{(solid carbonate mineral)}}$$ (M = divalent cation → Ca^{2+}, Mg^{2+}, Fe^{2+})



Calcite ($CaCO_3$) Magnesite ($MgCO_3$) Siderite ($FeCO_3$) Dolomite [$Ca,Mg(CO_3)_2$]

2. **Mineral Deposits Formation.** Hydrothermal transport of heavy metals (e.g., Cu, Zn, Pb, Mn, Fe) and better comprehension of Seafloor Massive Sulfide (SMS) deposits formation at different environmental conditions.



(a-c) Remotely Operated underwater Vehicle (ROV) Ægir 6000 (UiB) (videos) used for Deep Sea exploration, e.g., sampling of rocks/sulfide minerals and hydrothermal fluids; **(d-i)** SMS deposits associated with hydrothermal vent activity (pictures captured by Ægir 6000).

Marine Sustainability Context

Regarding the CO_2-basalt storage mechanism. Beside the well explored CO_2 storage within saline aquifers or depleted Oil and Gas fields, the permanent CO_2 storage by mineral trapping in basaltic rocks has huge potential and advantages. Basalts cover over 50% of the Earth's surface, making it the most abundant rock type in the Earth's crust. For Norway, and most Countries bordering the ocean, this highlights an encouraging prospective method for reducing atmospheric CO_2.

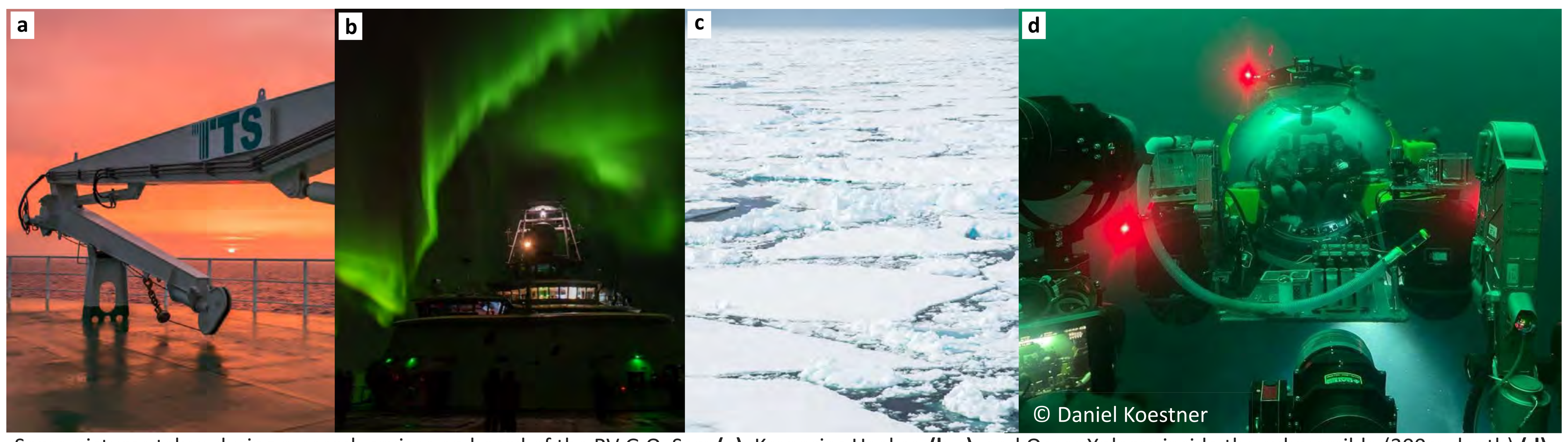
Results and Highlighted Activities

Internship

- Nov 2023 - Dec 2024. Equinor ASA, Sandsli, Bergen, Norway. *CO_2 storage maturation* project;

Scientific Research Cruises

- Arctic Polar Circle: **(1)** Molloy Deep trench, Greenland Sea (May 2022) on board the RV Kronprins Haakon (depature from Svalbard); **(2)** Mohns Ridge, Greenland-Norwegian Sea (Jun-Jul 2022) on board the RV G.O. Sars (departure from Bergen); **(3)** Knipovich Ridge, Greenland-Norwegian Sea (Nov 2022) on board the RV Kronprins Haakon (departure from Svalbard). Norway: **(4)** Norwegian Sea and Sognefjord (Jul-Aug 2023) on board the RV OceanXplorer (departure from Bergen): Video UiB & OceanX - Research Cruise in Norway (Web page OceanX / YouTube: Introducing OceanXplorer).



Some pictures taken during research cruises on board of the RV G.O. Sars **(a)**, Kronprins Haakon **(b-c)**, and OceanXplorer inside the submersible (300m depth) **(d)**.

Conferences

- Oct 26th - 27th 2022. Deep Sea Minerals Conference, Bergen, Norway (viewer); Jun 19th - 21th 2023. The 12th Trondheim Conference on CO_2 Capture, Transport and Storage, Norway (viewer); April 14th-19th 2024, EGU, Vienna, Austria.

Workshop

Aug 27th - Sep 1st 2023. NordVulk Summer School 2023 on CCUS in the Nordic countries, Iceland (Photos: Reykjanes Peninsula / Fagradalsfjall lava fields).

External Collaborations

- Nov 2022 - Sept 2023. Collaboration with Wild Space Productions (WSP) and Freeborne Media, two documentary production hubs based in Bristol (UK). Selection, description, and delivery of video footage showing Deep Sea environment for the episode that deals with the Arctic Ocean (some sequences from the episode just below) in the new five-part series "Our Oceans", premiering globally on Netflix in 2024. Visit in Bristol for *private premiere* of the episode on June 6th 2023 (UiB and Wild Space Productions with Netflix).

Other Projects

- 2023 - 2025. The audio-visual project *"Meditations on the Deep Sea"* in collaboration with SEAS colleague Daniel Koestner et al., OceanX and UiB (Video Clips: Netflix footage - Deep ocean - Red Sea - OceanX submersible).

Aim

The combination between my experimental work on CO_2-basalt storage (academic research goal) and the potential use of the laboratory results for the development of CCUS technologies in the field (internship goal) is the ultimate aspiration of my project.

Supervisory Team

Supervisor: **Ingunn Hindenes Thorseth**, UiB; Project Leader: **Rolf Birger Svarstad Pedersen**, UiB; External mentor: **Sascha Bussat**, Equinor ASA.

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