ÉCOLE DOCTORALE
SCIENCES DE LA TERRE ET DE L'ENVIRONNEMENT ET PHYSIQUE DE L'UNIVERS, PARIS

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Titre du sujet : Interactions fluide-manteau le long des failles transformantes océaniques

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PhD project motivations and questions

The circulation of hydrothermal fluids through the oceanic lithosphere, and associated alteration processes, is the first order control on Earth's volatile cycles and has been proposed as a potential driver of the emergence of life on our planet. Constraining where and to which extent the oceanic lithosphere is altered, and the consequences of hydrothermal alteration on the composition of the oceanic lithosphere, the associated carbon budget and prebiotic chemistry is thus key.

Hydrothermal circulation occurs at different geological settings, but most (65%) of the >500 known venting sites occur at mid-ocean ridges (MOR), other settings being back-arc spreading centers, submarine arc volcanoes and hotspot volcanoes (Frueh-Green et al., 2022). At MOR, hydrothermal circulation is driven by mantle melting, volcanism and faulting. Interaction of percolating fluids with deforming mantle rocks leads to the formation of trails of fluid inclusions in primary minerals (olivine and pyroxene; e.g., Klein et al., 2019; Andreani et al., 2023) and new hydrous phases (mainly serpentine, chlorite and amphibole), whose nature mainly depends on water-rock ratio and the temperature (i.e., depth) at which interaction takes place (Fig. 1a; e.g., Bickert et al., 2023a; Picazo et al., 2012). These alteration minerals are able to host large amounts of volatiles in their mineral structure, including water (~13 wt.% for serpentine) and fluid-mobile elements such as boron, chlorine, strontium (e.g., Scambelluri et al., 2004; Urann et al., 2017), having thereby a key impact on the Earth's volatile budget (e.g., for subduction zones; Rüpke et al., 2004; Scambelluri et al., 2019). Similarly, hydrothermal alteration, which leads to strong chemical desequilibria promoting redox reactions, significantly affects the carbon cycle, with the possibility of producing organic compounds from inorganic carbon (*e.g.*, CO/CO_2-bearing fluids). They will then co-evolve with mineral as hydrothermal alteration proceeds, leading to a potentially large diversity of organic compounds (e.g., hydrocarbons, organic- and amino- acids and condensed carbonaceous material) from magmatic or seawater carbon (Andreani et al., 2023; Andreani and Ménez, 2019; Lang et al., 2010; Ménez et al., 2018; Proskurowski et al., 2008; Sforna et al., 2018).

While hydrothermal processes have been relatively well studied at MORs, recent geophysical and geological observations also suggest deep hydrothermal fluid percolation on oceanic transform faults (OTFs). These overlooked strike-slip plate boundaries that segment MORs are indeed marked by lithospheric-scale low seismic velocity anomalies and high VP/VS ratios (Guo et al., 2018; Wang et al., 2022), which is consistent with studies on mantle rocks deformed and exhumed at OTFs of the Southwest Indian Ridge (SWIR) that indicate intense interaction of fault zone rocks with hydrothermal fluids down to at least 25 km depth (Fig. 1b; Prigent et al., 2020). Samples also reveal that fluid-rock interaction processes lead to a drastic change in the mineralogy and (micro)structure of the lithospheric mantle on OTF fault zones, with abundant crystallization of hydrous phases, similar to those formed at ridges (Fig. 1; Bickert et al., 2023; Kohli et al., 2021; Prigent et al., 2020). Klein et al. (2024) also recently found evidence of mineral carbonation of mantle rocks on the St Paul's Atlantic OTF with CO_2 interpreted as resulting from magmatic degassing in or below the root zone of the OTF. In contrast to classical models, this means that OTF could be partly magmatic and serve as conduits for CO_2-rich hydrothermal fluids potentially feeding organic synthesis never studied in these contexts. Abiotic organic synthesis could be promoted by H_2 resulting from fluid-peridotites reactions associated with the hydrothermal activity recently highlighted at OTFs. But the intense deformation associated with these plate boundaries could also favor the production of H_2 by comminution of the rocks (following the mechanochemical dissociation of water on the surfaces of deformed silicates), a mechanism as yet little explored at the level of the oceanic lithosphere.

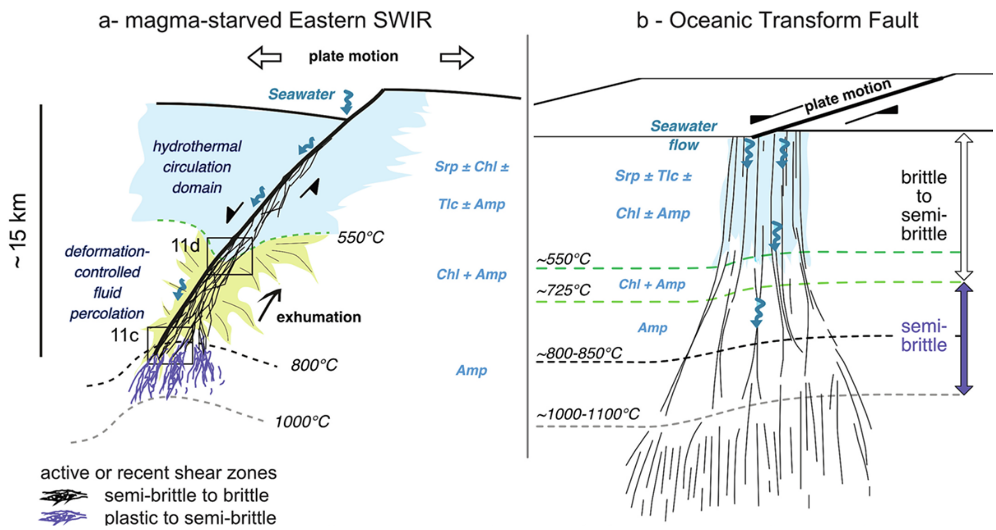

Fig. 1. *Interpretative sketches comparing hydration and deformation processes in the root zone of (a) the eastern Southwest Indian Ridge (SWIR) detachment faults (modified after Bickert et al., 2021) and (b) SWIR oceanic transform faults (modified after Prigent et al., 2020) from Bickert et al. (2023a).*

Based on these observations, this PhD project will consist in constraining the compositional consequences of fluid-rock interaction and deformation in the fault zone of OTFs, and their consequences on the deep carbon cycle and formation of organic compounds. It will aim at answering the following ***questions***:

- What is the composition of fluids percolating through the mantle at OTF fault zones and what are the consequences on the volatile budget of altered and deformed mantle rocks? How does it compare to hydrothermal fluid composition and volatile enrichment of mantle rocks on detachment faults associated with (ultra)slow spreading ridges?
- What is the diversity of organic compounds formed at OTFs? How are they formed and do magmatism and deformation and associated hydrothermal fluid circulation control their nature and distribution? If formed abiotically, what is the source of carbon and dihydrogen? How do abiotic organic compounds formed at OTFs and associated processed compared to those found at ridges?

Work plan and methodology

Objective1. Composition of fault zone rocks and hydrothermal dynamics on OTFs vs MOR detachment faults: insight from the ultraslow-spreading SWIR

To constrain hydrothermal processes and the composition of the mantle on OTFs, ultramafic samples that have been deformed, exhumed and collected on OTF fault zones will be characterized through integrated petrological-microstructural-geochemical studies. Samples come from two SWIR OTFs (Prince Edward and Shaka). They have been petrologically characterized by Prigent et al. (2020) and thin and thick sections of the samples are available at IPGP. Constraining the nature and composition (including fluid-mobile elements and volatiles) of phases crystallizing after fluid-rock interaction at varying depth along these OTFs (Fig. 1b) will allow to both quantify volatiles enrichment of the mantle and bring constraints on the nature and composition of hydrothermal fluids percolating through the mantle on these ultraslow-spreading OTFs. A similar work will be done on mantle rocks exhumed from detachment faults along the SWIR (Fig. 1a; Bickert et al., 2023a, 2021), from thin and thick sections of samples also available at IPGP. Results of mineral enrichment and fluid composition crystallizing at similar depths on OTFs and detachment faults will allow to compare the hydrothermal processes and dynamics on these two plate interfaces. Analytical work will include SEM-EDS, EPMA, LA-ICPMS and SIMS analyses of rocks.

If enough time, these compositional depth profiles will be reproduced through relatively simple hydrothermal circulation models that include reactive transport of elements (e.g., boron) as for instance those developed in McCaig et al. (2018). These models would bring constraints on some of the physical parameters associated with fluid flow on OTFs vs detachment faults, as fault zone permeability, duration of fluid-rock interaction or fluid percolation velocity.

Objective2. Inorganic vs organic carbon dynamics at OTFs and associated contributions of magmatism, rock deformation and hydrothermalism

To constrain the distribution, nature and formation mechanism(s) of carbon-bearing compounds forming at OTFs, the PhD student will analyze mantle rock samples deformed and exhumed from the root of OTFs segmenting fast- to ultraslow-spreading ridges. Based on OTF topography and results from numerical models, Tian et al. (2024) recently proposed that the amount of magmatism in an OTF domain increases with its slip rate. Studying mantle rocks deformed on OTFs with varying slip rates should thus allow determining the role of magmatism on the deep carbon cycle at these plate interfaces. Serpentine- and amphibole-bearing peridotite mylonite samples will come from the Pacific (Garrett OTF, ~130 mm/yr), the Atlantic (Vema and St Paul OTFs, ~30 mm/yr) and the SWIR (Pr. Edward and Shaka, ~10 mm/yr). Thin sections are available for most of the samples at IPGP; remaining ones will be subsampled in the rock repository of Ifremer in Brest. The composition of shear zones and fluid inclusions developing during deformation will in particular be constrained.

Analytical work will include bulk Rock-Eval and isotopic analyses, as well as FTIR, Raman, TOF-SIMS, and EDS mapping combined with FIB-EDS analyses in order to explore the presence, nature and distribution of carbonates, carbonaceous matter or adsorbed organic components in the shear zones developing during deformation of the rocks. EBSD analyses will be also performed if a link with intracrystalline deformation and organic compounds' distribution is revealed. To analyze the composition of fluid inclusions, Raman 2D and 3D mapping, FIB-EDS and TEM analyses will be used. The contribution and role of magmatism will be assessed through analyzing the composition of hydrous phases formed after fluid-rock interaction in all the samples (mainly amphibole) by LA-ICPMS.

Supervision

The PhD student will be supervised by Cécile Prigent and Bénédicte Ménez (IPGP), Muriel Andreani (Univ. Lyon 1, chercheuse associée IPGP) and Manon Bickert (Ifremer Brest).

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