# Fluids in the Earth's lithosphere: From petrology to geodynamics

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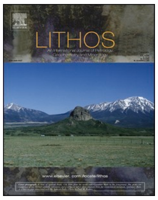

# Fluids in the Earth's lithosphere: From petrology to geodynamics

## 1. Introduction of the special volume

Fluids are ubiquitous in Earth's lithosphere. Reactions between fluids and rocks critically impact petrophysical rock properties and the geochemistry and geodynamics of the Earth at all scales. By enhancing reaction kinetics and mass transport, fluids play a fundamental role in geological processes from the Earth's surface down to the deep lithosphere. Lithospheric deformation in all tectonic settings is strongly influenced by fluids, which contribute to strain localization, earthquake nucleation, as well as potential rheological weakening or strengthening triggered by advective fluid flow and metasomatism. Multiple and complex feedbacks between host rock and percolating fluids are known to lead to the formation of economic mineral deposits in a great variety of tectonic settings from the seafloor to the roots of mountain belts. Fluids can also provide a favorable environment for life development in unexpected settings.

Nearly 45 years after the seminal textbook from Fyfe, Price and Thompson (1978) entitled ‘Fluids in the Earth's crust’, we intended with this special volume to provide a reflection of the current state-of-the-art and remaining challenges in the fields of petrology, geochemistry and on the feedbacks between fluids and hard rock processes at all scales in a range of tectonic settings. The thought-provoking contributions span a range of geological contexts from shallow oceanic and continental crust environments down to deeper, lower crustal and lithospheric mantle regions.

We hope that this volume will be of interest to the increasingly broader community that focuses on understanding the countless feedbacks between rocks from the lithosphere, and the great variety of fluids that contribute to shaping the Earth's surface and the emergence of life. Finally, we would like to express special thanks to the former Lithos editor Marco Scambelluri for his enthusiasm and initial support of this initiative. We also thank the current editor Nadia Malaspina for her assistance, for her patience and for her advice throughout the editorial process. We also warmly acknowledge the authors for their contributions, and also all the reviewers who substantially contributed to the completion of this volume thanks to their constructive comments.

## 2. Presentation of contributions

Hydrothermal circulation through the oceanic lithosphere at mid-ocean ridge (MOR) systems is an important process for mass and heat transfers between the solid Earth and the oceans. Associated fluid-rock interaction processes trigger hydrothermal reactions and the formation of new phases (e.g., serpentine in ultramafic lithologies at $T < 550$ °C) that modify the composition, rheology, and dynamics of both the crust and the mantle. They also lead to chemical modifications of the percolating fluids and mobilization of elements that can then precipitate and form ore deposits. The characterization of drilled samples from hydrothermal fields and rocks exhumed from detachment faults can provide crucial insight into the processes and depth of fluid percolation and fluid-rock interaction processes at MOR systems, and a better understanding of the genesis of hydrothermal ore deposits, the volatile content of the oceanic lithosphere and parameters governing the tectonic dynamics of these plate boundaries.

In **Pujatti et al.**, the authors investigate processes controlling the growth of the active sulfide mound at the basalt-hosted Trans-Atlantic Geotraverse (TAG) hydrothermal field. By combining petrographic observations of drilled samples with thermodynamic and sulfur isotope geochemical modelling, they suggest that the precipitation of nodular pyrite is coupled with anhydrite dissolution within the mound.

**Evans et al.** provide a state-of-the-art review of the relationships amongst fluids, ultramafic rocks, and alloys during serpentinization. They highlight that serpentinite-hosted alloys are widespread in a broad range of geodynamic settings, elaborate on the mobility of platinum-group elements during serpentinization, and emphasize the critical roles the oxidation of iron and the concomitant formation of molecular hydrogen play in stabilizing such extremely reduced minerals on Earth that are otherwise known mostly from meteorites.

From the examination of ultramafic rocks from the ultraslow-spreading Southwest Indian ridge, **Bickert et al.** determine the depth of fluid migrating along detachment faults. Their results suggest hydrothermal fluid percolation to unexpected depths, near the brittle-ductile transition. Hydrothermal alteration leads to the formation of amphibole-bearing deformed peridotites at depths above the stability limit of serpentine and to temperatures exceeding 800 °C.

Tremendous amounts of fluids are trapped in the oceanic lithosphere during its journey from the ridge to the trench. These volatiles are released during subduction via porosity collapse and metamorphic dehydration reactions down to sub-arc depths and beyond. Understanding the chemistry of these fluids and their effect on the lithosphere is fundamental for assessing fluid-rock interaction processes and for mass balance estimates of volatiles' recycling at a global scale. Exhumed high-pressure/low-temperature metamorphic terranes represent unique windows for deciphering ancient fluid-rock interaction events and refine our vision of the diversity of fluid chemistry and the effect of fluids on deformation processes. Clues on the chemistry of the fluids responsible for the various metasomatic events recorded in exhumed meta-ophiolites can be gained studying the mineral record but also the fluid inclusions trapped in these minerals.

In **Butjosa et al.**, the authors study an antigoritite block rim in a

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serpentinite mélange from central Cuba that shows evidence for hydrofracturing followed by precipitation of tremolitite and subsequent formation of chlorite-rich blackwalls. Petro-geochemical characterization of this sequence indicates that highly pressurized fluids of mixed sources reacted with the block upon exhumation in the subduction channel environment.

Using fluid inclusion data from a deep paleo-accretionary sequence in the Western Alps, **Herviou et al**. investigate the changes in fluid composition (with a special focus on salinity) in both metasedimentary and metamafic sequences. These authors identify trends in salinity as a function of metamorphic grade and discuss potential explanations for the evolution of fluid inclusion composition from seafloor to eclogite-facies conditions.

As a consequence of metasomatic processes, the formation of high-variance assemblages such as chloritites, tremolitites or talcschists could play an important role in the rheology of the subduction interface. In a field and petro-structural study on a subduction mélange in Japan, **Nishiyama et al.** emphasize the importance of actinolite-rich blackwall formation and deformation, on the rheology of the plate interface at the base of the megathrust region.

Focusing on shallower depths, **Boulton et al**. study an ancient thrust from a paleoaccretionary wedge in New Zealand and document frictional-viscous deformation mechanisms in calcareous mudstones at a few km depth, in the presence of fluid overpressures. Using fault rheology modelling and available observations, they identify frictional-viscous flow as a major weakening mechanism that may occur at temporally variable strain rates, governed by processes changing the diffusive distance, in the shallow part of the megathrust region.

Based on subduction zone thermal modelling, **McLellan et al.** calculate the theoretical fluid flux rates that occur during prograde metamorphism along the Cascadia margin. They relate the lateral variation of these fluid fluxes with tremor distribution and density in order to shed light on how the rates of pore fluid pressure buildup could control the rheology of the subduction interface.

The implementation of poro-elasticity equations in fully-coupled mechanical numerical models opens the possibility of reproducing the complex rheological fluid-rock feedbacks that occur in the roots of the megathrust region. In their study, **Dal Zilio & Gerya** managed to reproduce numerically complex sequences of ruptures, aftershocks and aseismic slip events, thus shedding light on the enigmatic rheology of fluid-saturated faults in the slow-slip earthquakes region.

Fluids released upon subduction processes also contributed to the shaping of continental lithosphere since archean times, in particular under continental arcs. The presence of fluids in aqueous form is known to have a significant impact on the crust's evolution, affecting its chemical and mineralogical reactions and its rheology. The long-term evolution of the crust and its protracted record of fluid flux can be identified using a variety of petrological and geochemical tracers as evidenced in the following studies.

The mechanism of gas fluxing into silicic magma reservoirs is explored by the **Scaillet** study. This paper uses experimental phase equilibria, thermodynamic relationships between gas and silicate melts, and heat balance on many types of magmas, at different pressures and at low $H_2O/CO_2$ ratios. Long-term fluxing of felsic to intermediate magma bodies stored in the upper crust by mafic volatiles will generally lead to isothermal solidification. Conversely, for bodies stagnating in the mid to deep crust, such a process almost inevitably enhances melting, driving or maintaining magmas beyond the mobility threshold needed for upward material transfer. Crustal growth in arc settings may be in part limited by the difficulty of crystallizing deep-seated magma bodies. This pressure-controlled effect is related to the contrasted solubilities of $H_2O$ and $CO_2$ in silicate melts, and to the much stronger non-ideal behavior of $CO_2$ relative to $H_2O$ as pressure increases.

The work of **Morales-Cámera et al**. deals with an issue related with the petrogenesis of granites and the contribution of fluorine-rich components in the fluid phase at the origin of A-type granites. They focus on the Early Carboniferous Andaluca pluton in Eastern Sierras Pampeanas in Argentina. The enrichment in F and HFSE elements suggests a fluorine-rich parental alkaline mafic magma involving the partial melting of a metasomatized sub-continental lithospheric mantle. The authors propose a model where asthenospheric melts and fluids metasomatize the subcontinental lithospheric mantle resulting in volatile-rich alkaline magma. After subsequent differentiation processes, fractionation and assimilation resulted in F-rich A-type granites.

In **Melfou et al**., the authors focus on Iron oxide-Copper-Gold deposits from the Nautanen locality in Sweden. They use the elemental and isotopic geochemistry of several generations of apatite grains from this deposit in order to highlight the presence of mixing and mutually-overprinting of various fluid sources and subsequent hydrothermal alteration. They also suggest that the host country rock can substantially alter apatite trace element signatures.

**Pauly et al**. report petrological and geochemical features of beryl as an indicator of metasomatic components in igneous and metasomatic processes. The authors have focused their study on granitic pegmatite from the California Blue Mine, USA, providing data on trace elements in beryl of different origins. Their conclusions deduced from beryl for pegmatites and miarolitic pockets and the comparison with an extensive database allow the authors to extrapolate their interpretations in order to use beryl as a petrogenetic indicator.

In **Zertani et al**., the authors combine petrophysical measurements on naturally deformed meta-granitic samples from various localities together with thermodynamic calculations to evaluate the seismic velocities of metamorphosed granitic crust and assess the contribution of anisotropy and fluid availability. They propose that it is not possible to differentiate felsic HP rocks from their protoliths because of minimal wave velocity changes.

The mechanisms and rate of metamorphic change in strong and dry lower crust are reassessed by **Jamtveit et al.**, using an example from the Lindås Nappe of Western Norway. Here, fluid-producing prograde metamorphism at the base of the nappe is interpreted to be driven by shear heating that enabled temperatures to reach wet melting. Concomitant fluid-driven retrograde metamorphism in the overlying crustal wedge is paired with this thermal and rheological transformation, evidenced by eclogite- and amphibolite-facies metamorphism of lower crustal granulites and the emplacement of voluminous pegmatites and dykes. These features demonstrate the importance of fluid production and interaction in controlling the patterns of metamorphism and deformation.

**Varga et al**. argue for a similar conclusion about the drivers for metamorphism and fluid-rock interaction in the mid- to lower-crust using the Entia Gneiss Complex of central Australia as a case study. In this example, the transformation of dry, strong and unreactive basement rocks is catalyzed by pervasive hydration and associated deformation that ultimately culminates in the formation of a migmatitic gneiss dome. Fluid is derived from the metamorphic dehydration of structurally juxtaposed supracrustal rocks during duplex formation, enabling previously anhydrous basement to repeatedly produce melt and undergo widespread deformation. The rheological response of the crust during orogenesis was thus fundamentally fluid-controlled, resulting in a close link between hydration, partial melting and structural reworking.

In **Putnis et al**., the authors investigate the preservation of granulites in the partially eclogitized and hydrated rocks from Holsnøy, Bergen Arcs, Norway. Granulite preservation has classically been interpreted to reflect metastability due to only limited fluid infiltration in the granulites. In this study, the authors provide an alternative explanation that considers the role of tectonic pressure variations on the development of eclogites in granulite terranes. Their model is motivated by the observation that granulites in Holsnøy were not eclogitized despite being partially hydrated, and is supported by thermodynamic modelling. Thus, this study contributes to the ongoing debate on the generation and magnitude of tectonic pressure variations in the lithosphere, which, in conjunction with fluid-rock interaction, can drive important metamorphic and rheological transformations.

The fluid-assisted processes leading to weakening and strain localization in the otherwise anhydrous and mechanically strong granulitic lower crust are investigated by **Tacchetto et al**. The authors have studied a shear zone in the Bergen Arcs, Norway, that exposes the transition from a weakly deformed coronitic anorthosite to a fine-grained amphibolite along a continuous strain gradient. By integrating phase equilibria modelling with electron backscatter diffraction and microstructural observations, the authors concluded that fluid infiltration in the anorthosite facilitated mineral reactions and deformation by dislocation creep, thereby promoting strain localization in the hydrated shear zone.

**Daczko & Piazolo** highlight the microstructural- and outcrop-scale signatures of *syn*-deformational melt migration pathways in high-strain rocks. They propose a set of diagnostic characteristics to identify melt migration pathways that develop in conjunction with high-strain deformation, and discuss the importance of melt-present deformation for rheological transitions, as well as for the potential effect on the localization of metasomatism, and for long-lived melt migration and chemical differentiation of the continental crust.

At the base of magmatic arcs and in the lithospheric mantle, a variety of fluid-rock interactions processes give rise to the formation of exotic and fascinating assemblages such as garnet peridotites, carbonatitic melts and lamprophyres as a consequence of slab-derived fluid-mediated chemical recycling and associated mantle metasomatism over millions of years. Such interaction between slab-derived components and the overlying mantle can be identified for instance using diamonds as revealed by the following studies.

Interaction between melts and fluids in the garnet-bearing mantle was investigated by **Shatskiy et al.** by means of experiments in a multi-anvil press at 6 GPa at temperatures ranging from 1200 to 1500 °C. This work focussed on the interaction between garnet lherzolite and two immiscible K-rich melts, $CO_2$-bearing phonolite and carbonate, derived by the partial melting of carbonated pelite. It is shown that the $CO_2$-bearing phonolite melt reacted to produce orthopyroxene and garnet at the expense of olivine, whereas $K_2O$ and $CO_2$ partitioned into the carbonate melt. Since the compositions of immiscible carbonatite and phonolite melts resemble carbonatite and silicate inclusions in natural diamonds, this work contributes to unraveling the origin of these melts and, therefore, the diamond origin related to a subduction setting or their formation in the peridotitic mantle.

In **Elazar et al.**, the authors focus on nitrogen characteristics and high-density fluid inclusions in fibrous diamonds from kimberlites from Nunavut territories (Canada). They identify various diamond populations, compare their N systematics, and propose a temporal connection as well as a genetic link for explaining their formation, with implications on our understanding of gem-quality diamonds.

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