Earth and Planetary Science Letters 484 (2018) 213–228

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

# Transfer of subduction fluids into the deforming mantle wedge during nascent subduction: Evidence from trace elements and boron isotopes (Semail ophiolite, Oman)

C. Prigent [a,*], S. Guillot [a], P. Agard [b], D. Lemarchand [c], M. Soret [b], M. Ulrich [d]

[a] Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre, 38000 Grenoble, France
[b] Sorbonne Universités, UPMC Univ. Paris 06, CNRS, Institut des Sciences de la Terre de Paris (ISTeP), 4 place Jussieu, 75005 Paris, France
[c] Laboratoire d'Hydrologie et de Géochimie de Strasbourg, EOST-CNRS-UMR 7517, Université de Strasbourg, France
[d] Institut de Physique du Globe de Strasbourg, EOST-CNRS-UMR 7516, Université de Strasbourg, France

ARTICLE INFO

*Article history:*
Received 10 April 2017
Received in revised form 26 November 2017
Accepted 6 December 2017
Available online xxxx
Editor: M. Bickle

*Keywords:*
boron isotopes
fluid migration processes
mantle wedge
metasomatism
ophiolite
subduction

ABSTRACT

The basal part of the Semail ophiolitic mantle was (de)formed at relatively low temperature (LT) directly above the plate interface during "nascent subduction" (the prelude to ophiolite obduction). This subduction-related LT deformation was associated with progressive strain localization and cooling, resulting in the formation of porphyroclastic to ultramylonitic shear zones prior to serpentinization.

Using petrological and geochemical analyses (trace elements and B isotopes), we show that these basal peridotites interacted with hydrous fluids percolating by porous flow during mylonitic deformation (from ~850 down to 650 °C). This process resulted in 1) high-T amphibole crystallization, 2) striking enrichments of minerals in fluid mobile elements (FME; particularly B, Li and Cs with concentrations up to 400 times those of the depleted mantle) and 3) peridotites with an elevated $\delta^{11}B$ of up to +25‰. These features indicate that the metasomatic hydrous fluids are most likely derived from the dehydration of subducting crustal amphibolitic materials (i.e., the present-day high-T sole).

The rapid decrease in metasomatized peridotite $\delta^{11}B$ with increasing distance to the contact with the HT sole (to depleted mantle isotopic values in <1 km) suggests an intense interaction between peridotites and rapid migrating fluids (~1–25 m.y$^{-1}$), erasing the initial high-$\delta^{11}B$ subduction fluid signature within a short distance. The increase of peridotite $\delta^{11}B$ with increasing deformation furthermore indicates that the flow of subduction fluids was progressively channelized in actively deforming shear zones parallel to the contact. Taken together, these results also suggest that the migration of subduction fluids/melts by porous flow through the subsolidus mantle wedge (i.e., above the plate interface at sub-arc depths) is unlikely to be an effective mechanism to transport slab-derived elements to the locus of partial melting in subduction zones.



## 1. Introduction

Element recycling in subduction zones plays a critical role on the geochemical budget and physical properties of the Earth. Lavas erupted above subduction zones display elemental and isotopic ratios that testify to the incorporation of a slab component to the mantle source of arc magmas (e.g. Morris et al., 1990; Plank and Langmuir, 1993; Tatsumi and Eggins, 1995). This slab signature is brought by the dehydration and/or the hydrous partial melting of subducting hydrated oceanic plates and the continuous transfer of solute-rich aqueous fluid and/or hydrous melt to the overlying mantle wedge. Knowing which elements are released during slab dehydration and how fluids and/or melts subsequently interact with the overlying mantle wedge is therefore crucial to understand the Earth's global geochemical cycle.

Boron (B) is a strongly fluid-mobile element (FME; Brenan et al., 1998) which may isotopically fractionate between fluids and minerals during (de)hydration processes, with $^{11}B$ having a generally higher affinity with fluid phases than $^{10}B$. It has thus been considered as a very good tracer for elucidating mass-transfer processes in subduction zones (e.g. Leeman and Sisson, 1996; Marschall et al., 2007; Morris et al., 1990; Peacock and Hervig, 1999; Scambelluri and Tonarini, 2012). The high B concentration and high $\delta^{11}B$ (i.e. $^{11}B/^{10}B$ ratio) of arc lavas (up to ~50 µg/g

* Corresponding author. Present address: Department of Geological Sciences, University of Delaware, Penny Hall, 255 Academy Street, Newark, DE 19716, USA.
*E-mail address:* cprigent@udel.edu (C. Prigent).

https://doi.org/10.1016/j.epsl.2017.12.008
0012-821X/

and +18‰; Ishikawa and Tera, 1997; Tonarini et al., 2011) are interpreted as being part of the slab signature because the Depleted MORB Mantle (DMM) has low B concentration and $\delta^{11}$B (∼0.077 μg/g and −7.1‰; Marschall et al., 2017). The subducted altered oceanic crust and its sedimentary cover are known, however, to release fluids with high $\delta^{11}$B to the fore-arc shallow mantle and progressively more negative values at sub-arc depths, even lower than those of the DMM (Benton et al., 2001; Marschall et al., 2007; Peacock and Hervig, 1999). To account for the high $\delta^{11}$B of arc magmas, Scambelluri and Tonarini (2012) suggested that the high $\delta^{11}$B fore-arc serpentinites resulting from the hydration of the mantle wedge peridotites at ∼30 km depth are transported down the subduction interface to arc-depths, where serpentine breaks down.

In nascent intra-oceanic subduction zones (leading to ophiolite obduction), the basal mantle of the future ophiolite is located just above the subduction interface (e.g. Spray, 1984; Wakabayashi and Dilek, 2000; Agard et al., 2016). Ophiolites thus provide well-preserved examples of shallow (<40 km deep) incipient mantle wedges, the best documented being the Semail ophiolite (Oman, UAE). Basal peridotites from this ophiolite were affected by relatively low-temperature ductile deformation (∼650–850 °C, according to Linckens et al., 2011) and coeval subduction-related metasomatism (Khedr et al., 2014; Yoshikawa et al., 2015), before moderate serpentinisation. The study of the Semail basal peridotites can therefore provide essential information on (1) the composition of fluids released in a hot subduction zone, (2) mechanisms of slab-mantle wedge fluid transfer and fluid percolation through a hot mantle wedge, (3) subsequent fluid(s)–mantle wedge peridotite interactions and their influence on the fluid composition, and (4) the contribution of peridotitic protoliths to later mantle wedge serpentinite composition. We herein present and discuss geochemical (trace elements and B isotopes) analyses of whole rocks and constitutive minerals of basal peridotites and metamorphic sole rocks of the Semail ophiolite.

## 2. Geological setting and sample description

### *2.1. Geological setting*

The Semail ophiolite represents a well-preserved fragment of oceanic lithosphere obducted onto the Arabian continental passive margin, at the outcome of a convergence process initiated through intra-oceanic underthrusting (e.g. Boudier et al., 1988) or subduction (e.g. Searle and Cox, 1999). Since age constraints for the formation of the Semail oceanic crust and of the metamorphic sole are close (∼94.5–96.5 Ma; e.g. Hacker et al., 1996; Rioux et al., 2016), authors still debate on whether underthrusting/subduction predates (MacLeod et al., 2013; Searle and Cox, 1999) or shortly postdates (Boudier et al., 1988; Goodenough et al., 2014) the accretion of the main magmatic V1 sequence (Fig. 1b). All authors nevertheless agree that the basal mantle of the ophiolite and the underlying metamorphic soles were deformed, cooled and stacked together during the first millions years after the initiation of convergence, a tectonic stage referred to here as nascent subduction or “subduction infancy” (Fig. 1a; Agard et al., 2016 and references therein). These two units are therefore direct witnesses of early subduction dynamics.

The Semail metamorphic sole is interpreted as a relic of crustal material from the subducting plate heated (and metamorphosed) during its descent into the mantle (e.g. Hacker et al., 1996). The metamorphic sole is composed of at least two units. The upper High Temperature (HT) sole, composed of the juxtaposition of two sub-units of amphibolites to granulites, formed at higher temperature and depth (800 ± 100 °C and 1.0 ± 0.2 GPa) than the lower Low Temperature (LT) sole (550 ± 50 °C and 0.5 ± 0.1 GPa), made of upper greenschist to lower amphibolite facies metasediments and metabasalts (e.g. Soret et al., 2017).

The Semail ophiolitic mantle experienced two distinct stages of ductile deformation. A first HT deformation event, affecting the whole mantle section (at >1200 °C; e.g. Dygert et al., 2017; Nicolas et al., 2000), relates to the accretion of the main V1 magmatic unit. A second LT deformation, mainly observed at the base of the mantle, resulted in the development of a porphyroclastic to ultramylonitic basal shear zone of <3 km thickness (Fig. 1b; Boudier et al., 1988; Lippard et al., 1986; Nicolas et al., 2000; Searle, 1980). Mylonites and ultramylonites associated with this LT event are mostly observed in the first 200–500 m above the basal contact, forming the so-called “banded unit” (Fig. 1b). Temperature estimates for the LT deformation event have been constrained by Linckens et al. (2011) and Prigent et al. (in press) and indicate progressive strain localization under cooling: ∼1200 °C for the porphyroclastic deformation, ∼850–750 °C for the (proto)mylonitic deformation and ∼750–650 °C for the ultramylonitic deformation (Fig. 1c). Since tectono-metamorphic conditions of the LT mylonites are similar to those of the underlying HT sole, the proto- to ultramylonitic deformation of the banded unit peridotites and HT sole are regarded as coeval: shearing and cooling of the basal mantle occurred during nascent subduction (Agard et al., 2016; Boudier et al., 1988; Lippard et al., 1986; Searle, 1980), when this basal mantle was located just above the deforming subduction interface (Fig. 1a).

Processes of cryptic and modal metasomatism, at variable temperature conditions, were sparsely documented in these basal peridotites. LT metasomatism (prior to basal peridotite serpentinisation) is marked by FME enrichment of peridotitic minerals (Khedr et al., 2014; Prigent et al., in press; Yoshikawa et al., 2015) and by the crystallization of metasomatic minerals in the finer-grained olivine matrices of basal peridotites. These metasomatic phases are HT amphibole (pargasite to magnesio-hornblende; Khedr et al., 2014) and secondary olivine, clinopyroxene, orthopyroxene ± spinel (Fig. 1c; Prigent et al., in press). This LT metasomatism has been interpreted as the result of the interaction of banded unit peridotites with aqueous fluids released during metamorphic sole dehydration (Khedr et al., 2014; Prigent et al., in press; Yoshikawa et al., 2015).

### *2.2. Sampling and petrography*

We collected and studied 36 samples from the basal peridotites and the metamorphic sole across the ophiolite strike, in six massifs where basal sections have not been dismembered (preserving the following structural organization: banded unit peridotites/HT sole/LT sole units; Fig. 1b). Deformation in the banded unit peridotites can be heterogeneous, with lenses of porphyroclastic peridotites alternating with (ultra)mylonitic shear zones parallel to the basal contact and the HT sole foliation. Fully serpentinised peridotites are only found just above the contact with the metamorphic sole, over a few meters. Upsection, serpentine is rather found as veins crosscutting the foliation of the peridotites.

Ultramafic samples (Table 1) comprise 20 banded unit peridotites collected at different distances from the basal contact and affected by variable LT deformation intensities, 6 basal serpentinites and 2 HT peridotites located at >1 km above the basal contact (from Fizh and Kwar Fakkan massifs). The different banded unit peridotite textures, from LT porphyroclastic tectonites to LT ultramylonites (see Table 1), were identified through microscopic observations and named according to the classification of Linckens et al. (2011; Fig. 1c). Eight samples from the HT sole of the Fizh massif were also selected at different distances from the peridotites (Fig. 1b; Table 1).