Does Anisotropy of Thermal Contraction Control Hydrothermal Circulation at the Moho Level below Fast Spreading Oceanic Ridges?

FRANÇOISE BOUDIER, ADOLPHE NICOLAS, AND DAVID MAINPRICE

CNRS/UMII, Laboratoire de Tectonophysique, UMR5568, Université Montpellier II, Place. E. Bataillon, 34095 Montpellier, France

Abstract

It has been proposed that deep, high-T (up to 1000°C) hydrothermal alteration occurred within the gabbro section, near the paleo-ridge axis in the Oman ophiolite. In the deep, hot gabbros, the main water channels are submillimetric microcracks with a dominantly vertical orientation (Nicolas et al., 2003). Sr and O isotopic investigations point to seawater as the most likely hydrothermal contaminant (Bosch et al., 2004). It was proposed that the mechanism for seawater ingression at temperatures above 700°C was anisotropy of thermal contraction in gabbros, opening microcracks that are controlled by crystallographic fabrics. The exceptionally large anisotropy of thermal contraction of single-crystal calcic plagioclase, when combined with the lattice fabrics of the gabbros, results in the largest thermal contraction being parallel to the mineral lineation, which is itself normal to the ridge, thus inducing vertical fractures parallel to the ridge plane. High-T hydrothermal alteration in gabbros extends to the Moho. Interestingly, in the underlying peridotites, with a dominantly horizontal foliation, the direction of largest thermal contraction, calculated as above from fabrics and thermal expansion coefficients of olivine, is vertical, potentially responsible for subhorizontal cracking. Thus, during the off-axis drift of newly accreted lithosphere, at the limits of the axial magma chamber, thermal contraction opens vertical cracks in the crustal gabbros, favoring seawater ingression down to the Moho. Just below the Moho, the horizontal cracking preferred orientation could be closing the high-temperature hydrothermal circuit at this level. At temperatures below 700°C, oceanic ridge spreading–related tensile stress is dominant, inducing ridge-parallel cracking in both the crust and lithospheric mantle. Circulation of seawater-derived fluids in the Moho transition zone at gabbro solidus conditions should have important consequences for magmatic processes.

Introduction

HYDROTHERMAL CIRCULATION near fast spreading oceanic ridges typically operates below the ridge axis down to the base of the sheeted dike complex and penetrates the entire crust once it has drifted away from the ridge axis and has been cooled to greenschist facies conditions (T < 450°C). These conditions are referred as low-temperature (LT) conditions in this paper that deals with higher-temperature hydrothermal circulation developing close to the ridge axis.

Since the first record of deep and high temperature hydrothermal alteration in the gabbro section of the Wadi Tayin area in the Oman ophiolite (Gregory and Taylor, 1981; Lamphere, 1981; McCulloch et al., 1981) based on strontium and oxygen isotope tracing, the possibility of deep penetration of seawater close to the axis of fast spreading ridges has been underestimated. One reason was the difficulty of integrating such deep circulation in the framework of the wing-shaped magma chamber accepted in their model. Improved seismological modeling of fast spreading ridges at the East Pacific Rise led instead to a much smaller magma lens overlying a low-velocity zone (LVZ) (Detrick et al., 1987; Harding et al., 1989; Vera et al., 1990). At the same time, Nicolas et al. (1988) proposed, on the base of extensive structural studies in Oman, a tent-shaped magma chamber extending the partially molten domain, corresponding to the LVZ, down to the base of the crust (Fig. 1). This conceptual model is consistent with seismological models, assuming that the LVZ was deforming as a crystal mush, containing
more melt (15–25% for Mainprice, 1997) than first proposed.

Recently the concept of deep, high-temperature (HT) hydrothermal circulation at the limits of the magma chamber has been revisited following the study of high-T vein systems in gabbro samples drilled at Hess Deep in the crust of the East Pacific Rise (Manning et al., 1996; Lecuyer and Reynard, 1996). Applying this discovery to the Oman ophiolite, Manning et al. (2000) developed a model of hydrothermal alteration reaching the Moho ~6 km away from the axis, at a temperature of ~825°C, well above the 550°C cracking front estimated by Lister (1974). Nicolas et al. (2003), supported by new isotopic geochemistry (Bosch et al., 2004), studied the ubiquitous, pervasive HT hydrothermal alteration throughout the gabbro section of the Oman ophiolite. Very high temperature (VHT, ~1000°C) to high temperature (HT, ~700°C) conditions were recorded for this hydrothermal alteration. Hydrous gabbroic dikes relayed by lower-temperature green veins, dominantly parallel to the paleo-ridge plane, were mapped and identified as the discharge system of this hydrothermal circulation. Microcracks observed at the mineral aggregate scale, and operating from VHT to HT conditions, were ascribed to the recharge system.

Nicolas et al. (2003) calculated the anisotropy of thermal contraction in the gabbro aggregate using the crystallographic fabrics of plagioclase, the modal composition of the gabbro, and the anisotropy of thermal expansion of single-crystal calcic plagioclase, which is extremely large, up to 109% (Willaine et al., 1974). The calculated anisotropy of thermal contraction of the gabbro aggregate is high (~50%), and the direction of maximum contraction lies close to the mineral lineation. With decreasing temperature, this anisotropy could generate a tensile stress large enough to induce fracturing, even above the brittle-ductile limit. The fractures are perpendicular to the mineral lineation, which in gabbros has been developed by suspension flow in the magma chamber. This flow is dominantly at a large angle to the ridge plane (Fig. 1) and, consequently the fractures are on average, vertical, and parallel to the paleo-ridge plane. It was proposed that thermal anisotropy was responsible for the cracking of lower gabbros. In the present paper, we conduct a similar investigation in the upper-mantle peridotites exposed near the Moho transition zone (MTZ), combining this analysis with that of the VHT-HT cracking in the gabbros.

**Thermally Induced Microcracking in Peridotites**

We have calculated the anisotropy of thermal contraction in three peridotites representative of the MTZ and shallow underlying mantle, using the same procedure as in the gabbros. The calculation
procedure is described in the Appendix. Two dunite samples belong to the thick (up to 600 m) MTZ overlying the Maqsad diapir (Boudier and Nicolas, 1995): samples 83OF2 and 91OA130 are strained dunites with a horizontal foliation, located in the center and at the base of the MTZ, respectively. The third sample is a harzburgite collected 2 km below the Moho, in the mantle section of the Wadi Tayin massif.

The necessary physical parameters are the anisotropy of thermal expansion of single-crystal forsterite and enstatite, the peridotite fabrics, and the modal composition of the considered specimen. The studied dunites contain 1% spinel and 3% interstitial plagioclase, respectively; their olivine lattice preferred orientation (LPO) is strong (Figs. 2A and B) and typical of plastic flow at peridotite solidus conditions, with a strong point maximum of [010] perpendicular to foliation and a strong [100] maximum slightly oblique to mineral lineation. The studied harzburgite has a standard modal composition: olivine 68%, orthopyroxene 32%, and less than 1% spinel. Its mineral fabric (Fig. 2C) is typical of plastic flow in mantle harzburgites. Olivine has a strong LPO with a [100] point maximum at a low angle to the lineation and a more diffuse [010] maximum perpendicular to the foliation; orthopyroxene has a weaker fabric with a diffuse maximum of [100] trending parallel to [010].

Bouhifd et al. (1996) have studied the anisotropy of thermal expansion of single-crystal forsterite between 1890°C and room temperature. This anisotropy increases with temperature, reaching a value of about 45% at T = 900°C, and the direction of maximum expansion is parallel to [010] (Fig. 3A). The calculated anisotropy of thermal expansion of the studied samples of dunite is relatively high, 23.1 and 19.6 for the two specimens, respectively (Fig. 3B), and the largest thermal contraction is parallel to [010] olivine maximum—that is, subperpendicular to the foliation.

For the harzburgite specimen, we have calculated first the thermal anisotropy of the sample neglecting the contribution of enstatite (Fig. 3C), providing results similar to those obtained for the two dunites, thermal anisotropy = 19.4% and largest contraction subperpendicular to the foliation. The anisotropy of thermal expansion of enstatite is low (7.7% at T = 900°C), according to the data of Jackson et al. (2003), and the direction of maximum contraction is b = [010]. The calculated thermal anisotropy of the harzburgite sample integrating the contribution of enstatite is lowered to 13.2%, but the direction of maximum contraction is not changed, subperpendicular to the foliation. Thus from the three samples studied, the differential stress due to anisotropy of thermal contraction would induce cracking subparallel to the peridotite foliation, and the anisotropy of dunite is twice that of harzburgite.

**VHT-HT Hydrothermal Alteration in the Mantle Section**

VHT hydrothermal alteration in gabbros has been identified by reactions developing orthopyroxene at the contact between olivine and plagioclase and brown hornblende in clinopyroxene. HT alteration is marked by chloritization of olivine and development of green hornblende in clinopyroxene. The reacting minerals provide an isotopic record of seawater contamination (strontium and oxygen) at temperatures from 850° to 1000°C (Bosch et al., 2004). The VHT alteration increases down section in the gabbros, whereas the HT decreases downward (Fig. 4). The third parameter in Figure 4, “no alteration of olivine,” increasing down section indicates a decrease of the fluid/rock ratio with depth.

It is difficult to trace this alteration in the harzburgites from the mantle section. A possible record of HT hydrothermalism is the development of talc from enstatite (500°–700°C), that is present in mantle sections of the Oman ophiolite (Ceuleneer, 1986) and is correlated with fractures associated with ridge tectonics. In the MTZ, it is possible to trace the effects of VHT-HT hydrothermalism, due to the presence of gabbro sills interlayered with residual dunite, the main component of the thick MTZ. Systematic study of the VHT-HT hydrothermal alteration (Fig. 4) shows that VHT hydrothermal alteration is developed in the gabbro sills from the MTZ in the same range as in the lower gabbros, in contrast with HT alteration, which decreases in the MTZ, as well as the fluid/rock ratio, inferred from the rate of alteration of olivine (Bosch et al., 2004).

Detailed petrological and geochemical study of the thick MTZ overlying mantle diapirs also suggests that seawater may have penetrated at VHT near the ridge. It is a level of intense melt-rock interactions below the axial magma chamber (Boudier and Nicolas, 1995; Godard et al., 2000; Koga et al., 2001), recorded by the development of interstitial clinopyroxene and/or plagioclase in strongly depleted facies, orthopyroxene-poor harzburgites, and dunites. Preliminary isotopic data
FIG. 2. Lattice preferred orientation (LPO) of olivine in (A) dunite 83OF2 and (B) dunite 91OA130 from the thick MTZ overlying the Maqsad diapir. C. LPO of olivine and orthopyroxene in harzburgite sample 97OA129, 2 km below the Moho, Wadi Tayin massif. U-stage measurements, lower hemisphere of projection, refer to the foliation plane (E-W tracing) and mineral lineation (X direction).
on clinopyroxenes from cpx-bearing dunites and pyroxenites (Monteillet, 2000) show a high stron-
tium content and high $^{87}\text{Sr} / {^{86}}\text{Sr}$ ratio, interpreted as a contamination of clinopyroxene at its temperature of crystallization by seawater-derived fluids. The input of seawater-derived fluids at the temperature of crystallization of tholeiitic magmas has consequences that are not yet explored, like the change of the field of stability of coexisting minerals or increase in the oxygen fugacity of the crystallization medium (Koepke et al., 2003).

The latter effect, increase of $f_{O_2}$ due to water ingestion at the temperature of crystallization of magma, could bring chromite to the basaltic liquidus and favor chromite precipitation. The occurrence of hydrous phases like amphibole or epidote

Fig. 3. A. Anisotropy of thermal expansion of single-crystal forsterite (Bouhifd et al., 1996) and of enstatite (Jackson et al., 2003); a = [100], b = [010]. B. Calculated anisotropy of thermal expansion in dunite 83OF2 and dunite 91OA130, using LPOs of Figure 2A. C. Calculated anisotropy of thermal expansion of harzburgite 97OA129, using LPOs of Figure 2B, calculated with 100% olivine, 100% enstatite, and according to the sample modal composition, 68% olivine + 32% enstatite. The same reference system is used for (B) and (C) as in Figure 2.
in some refractory chromite nodules of the many chromitite deposits localized in the MTZ has been noted (i.e., Augé and Roberts, 1982), suggesting seawater ingression at the origin of chromite nucleation.

**Peridotite Fabrics and Serpentinitization**

Upper mantle peridotites in the Oman ophiolite, as well as those exposed or drilled at shallow depth (some hundreds meters) below the ocean floor of the Hess Deep near the East Pacific Rise (Gillis et al., 1993), or in the MARK area of the Mid-Atlantic Ridge (Mével et al., 1991) present a primary fabric inherited from asthenospheric plastic flow recorded by lattice preferred orientation (LPO) of olivine and orthopyroxene, and a subsequent fabric related to the penetrative serpentine lizardite network. All peridotites from the shallow suboceanic mantle are affected by serpentinization, whose rate, based on correlation with density measurements (Christensen, 1966), cluster between 30 and 60% for drilled samples from Hess Deep (Iturrino and Christensen, 1990) and for samples collected in Oman (Dewandel, 1996).

Dewandel et al. (2003) have explored possible relationships of the penetrative lizardite network with the primary olivine and orthopyroxene LPO, in

Fig. 4. Compilation of hydrothermal alteration features as a function of depth in the gabbro section and the MTZ, based on 500 thin sections covering the total surface of the Oman ophiolite (Bosch et al., 2004). Percentages represent the occurrence of a given type of alteration versus the number of thin sections examined for each selected level. Abbreviations: sd = sheeted dikes; gb = gabbros; MTZ = Moho transition zone. Alteration at very high temperature (VHT) is recorded by orthopyroxene coronas between olivine and plagioclase + brown hornblende around olivine and clinopyroxene. Alteration at high temperature (HT) is marked by partial or total replacement of olivine by chlorite and actinolite + partial replacement of clinopyroxene by green hornblende. The parameter “Ol core” measures the fraction of olivine that is not altered; a high ratio corresponds to a low volume of fluid.
the harzburgite sample selected for the present study (97OA129). The serpentinization (60%) develops pseudomorphic mesh textures, and veins of chrysotile and calcite that infiltrate the mesh network (Fig. 5A). Microveins forming the mesh texture are filled with lizardite having its basal (001) plane parallel to the margin of the microveins. Optical measurements of lizardite vein orientations show that the lizardite network is composed of two populations (Fig. 5B). One set is parallel to the (010) olivine maximum (see Fig. 2C), and slightly oblique to the foliation; the second set is perpendicular to the foliation, and its pole forms a girdle in the foliation plane with two submaxima parallel and perpendicular to the lineation.

Repeated field observations in the Oman ophiolite, representative of a fast spreading situation, show that in areas where the peridotite foliation is horizontal, it is underlain by a penetrative parting due to serpentine veining, in addition to a vertical parting perpendicular and parallel to the lineation respectively, which has been documented, in particular, in the Hilti massif (Ildefonse et al., 2001). This geometry, only valid for areas devoid of ridge tectonics, is consistent with the preferred orientation deduced above from measurements on specimen 97OA129 (Dewandel et al., 2003). These regular partings related to the serpentine network reveal the geometry of hydrothermal circulation in the LT conditions where serpentine minerals form.
We will discuss two problems in the framework of a newly created oceanic lithosphere drifting away from a fast spreading ridge. In the Oman ophiolite, the spreading geometry is recorded by the mantle flow-related foliation, which is horizontal in the very shallow mantle, and by mineral lineation representing the flow line, which is perpendicular to the ridge plane (Nicolas et al., 2000).

Closure of the VHT-HT hydrothermal circuit in the mantle

From earlier results noted above (Nicolas et al., 2003; Bosch et al., 2004), it is documented that seawater-derived fluids pass through the entire crust and reach the Moho, thanks to vertical ridge-parallel microcracks active in VHT-HT conditions, and that at these temperatures, microcrack opening is controlled by the anisotropy of thermal contraction in gabbros. Using a similar approach, we have calculated here this anisotropy in peridotites. Although weaker than in gabbros, this anisotropy should open cracks, and could explain seawater ingestion in the mantle. In peridotites, the direction of maximum contraction induces microcracking in planes subparallel to the foliation, which is dominantly horizontal at the scale of the entire ophiolite. Thus, in contrast with the situation in gabbros, thermally induced microcracks would be here horizontal, channeling the seawater flow horizontally and not vertically as in gabbros, thus impeding its penetration deep below the Moho (Fig. 6).

Nicolas et al. (2003) concluded that deep seawater recharge in the gabbros have implied the relay of (1) thermally induced contraction operating between 700°C and 1100°C and (2) ridge-related lithospheric tensile stress operating at a temperature below ~700°C, the brittle-ductile limit. The resulting cracking has the same geometry in both conditions, parallel to the oceanic spreading ridge. In the case of shallow mantle flowing horizontally, the geometry of cracking induced by tectonic stress at a temperature lower than 700°C is also parallel to the spreading ridge and vertical. In contrast, thermally induced cracking between 700°C and 1100°C should be horizontal. Thus in the very shallow mantle, the VHT-HT fluids crossing the Moho would be channeled horizontally and presumably should close the hydrothermal circuit. Below ~700°C, taken as the brittle-ductile limit, tectonic stress inducing vertical fracturing would become dominant, driving seawater-derived fluids deeper in the lithospheric mantle, and increasing its cooling rate.

Serpentinization

Mesh-textured lizardite, induced by LT hydrothermal alteration of the peridotites, develops below 500°C (Bowen and Tuttle, 1949; Seipold and Schilling, 2003), in conditions below the brittle-ductile limit. Thus tectonic stress could influence the cracking system responsible for mesh-textured serpentine. This spreading-related stress would account only for the vertical fracturing, not for the horizontal set of lizardite veins parallel to the preferred orientation of (010) olivine in peridotites.
We suggest that the horizontal veining is explained by thermal cracking produced at higher temperature. Thermally induced cracking may develop, as in the crustal gabbros in the VHT-HT field, but inasmuch as olivine does not undergo hydrous alteration at low hydrostatic pressure above ~600°C, the microcracks should preserve seawater until cooling below the thermal limit of stability of lizardite. The geometry revealed by the lizardite mesh texture suggests that both thermally induced and tectonic stresses have controlled the development of the lizardite network.

Conclusions

At fast spreading rates, the anisotropy of thermal contraction is a good candidate to explain seawater-derived fluid ingression at very high temperature, that is between 1100° and ~700°C, throughout the oceanic crust down to the mantle. Thermally induced microcracks constitute the recharge circuit of a VHT hydrothermal circulation. The calculated anisotropy reaches 20% in mantle peridotite, and is able to open microcracks parallel to the foliation, that is horizontal during normal off-axis mantle flow. This analysis complements a similar approach in the gabbro section, pointing out that high anisotropy of thermal contraction (reaching 50%) induces a ridge axis–parallel cracking that operates at decreasing temperature starting from 1100°C. Crossing the entire gabbro section, the hydrothermal circuit would be closing in the MTZ, a few hundreds of meters below the Moho, where it would interfere with magmatic processes and melt-rock reactions documented at this most active level.

Below the cracking front, 550°C for Lister (1974) and 700°C for Manning et al. (2000), ridge-related tensile stress controls the fracturing, which is then parallel to the spreading ridge in both crust and shallow mantle. The LT recharge hydrothermal circuit penetrates deeper in the lithospheric mantle, where its network is recorded by mesh-textured lizardite serpentine, which in Oman affects the total thickness of the detached lithospheric plate (up to ~10 km below the Moho).

Acknowledgments

Our studies in Oman began after Bob Coleman introduced us to this exceptional ophiolite in 1979. It is a pleasure to acknowledge him for his generous support to the entire community interested in oceanic lithospheric processes. Field campaigns were conducted thanks to the hospitality of the people and authorities of Oman, and particularly the Ministry of Commerce and Industry. Financial support was received from the Centre National de la Recherche Scientifique, from the Institut Universitaire de France, and from the French Embassy in Muscat. Reviews by Nikolas Christensen and Javier Escartin have substantially improved the manuscript.

REFERENCES


Gillis, K., Mével, C., Allan, J., et al., 1993, Proceedings of the Ocean Drilling Program, Initial Reports, Program 147: College Station, TX, Ocean Drilling Program.

Godard, M., Jousselin, D., and Bodinier, J. L., 2000, Relationships between structure and geochemistry in the mantle section of the Oman ophiolite: An ICP-MS


Appendix

We used the fabric data of olivine and enstatite from two Oman dunites and one harzburgite to evaluate the thermal expansion of these rocks. The calculation procedure for second-order tensor physical properties, such as thermal expansion, is as follows: (a) the grain orientation (or rotation) matrix \((g_{ij})\) is defined by the three Euler angles from the universal stage data; (b) the single-crystal tensor property \((T_{ij})\) is rotated into the grain orientation using \(T'_{ij} = g_{ik} \cdot g_{jl} \cdot T_{kl}\); (c) the tensor properties for each grain \((T'_{ij})\) are summed to give the aggregate property either using the Voigt average, sometimes called Hill or Voigt-Reuss-Hill average; (d) the aggregate tensor property \(T_{ij}\) can then be evaluated \((T)\) in any direction \((X_i)\) by \(T = T_{ij} \cdot X_i \cdot X_j\).

The thermal expansion is a strain \((\varepsilon_{ij})\) which is given by \(\varepsilon_{ij} = \alpha_{ij} \Delta T\), where \(\alpha_{ij}\) is a second-rank tensor of coefficients of thermal expansion and \(\Delta T\) is the change in temperature. The coefficients of thermal expansion tensor \(\alpha_{ij}\) depends on temperature, and the coefficients are in general only valid for a limited temperature range. For orthorhombic symmetry only the diagonal elements of a second-order tensor are non-zero—that is, \(\alpha_{11}, \alpha_{22},\) and \(\alpha_{33}\).

The principal thermal expansion coefficients \((\alpha_{11}, \alpha_{22},\) and \(\alpha_{33}\)) define the axial lengths of a representative quadric, which is an ellipsoid in the present case. The axes of the ellipsoid are parallel to the orthogonal cell edges in \(a[100], b[010],\) and \(c[001]\) directions. For olivine we have used high-temperature cell parameters of forsterite given by Bouhifd et al. (1996) to calculate the thermal expansion coefficients \(\alpha_{11} = 9.4 \times 10^{-6}\, ^\circ\text{C}^{-1}, \alpha_{22} = 14.8 \times 10^{-6}\, ^\circ\text{C}^{-1},\) and \(\alpha_{33} = 11.8 \times 10^{-6}\, ^\circ\text{C}^{-1}\) valid for the temperature range 600–1000°C. For enstatite we have used the most recent high-temperature cell parameters given by Jackson et al. (2003) to calculate the thermal expansion coefficients \(\alpha_{11} = 11.5 \times 10^{-6}\, ^\circ\text{C}^{-1}, \alpha_{22} = 11.8 \times 10^{-6}\, ^\circ\text{C}^{-1},\) and \(\alpha_{33} = 11.0 \times 10^{-6}\, ^\circ\text{C}^{-1}\) for the same temperature range as forsterite.

We note that the previously published thermal expansion data for enstatite and other orthopyroxenes show a considerable variation in magnitude and anisotropy; see Jackson et al. (2003) for further references.

\[
\bar{T}^{\text{Voigt}}_{ij} = \frac{\sum_{i=1}^{N} T'_{ij}}{N},
\]

or the Reuss average,

\[
\bar{T}^{\text{Reuss}}_{ij} = \left[ \frac{\sum_{i=1}^{N} T^{-1}_{ij}}{N} \right]^{-1}.
\]