Geochemical variability of the Oman ophiolite lavas: Relationship with spatial distribution and paleomagnetic directions

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[1] The multielemental composition of 31 lavas sampled in the extrusive section of the Oman ophiolite was determined by inductively coupled plasma-source mass spectrometry (ICP-MS). This study allowed us to define clear geochemical criteria to characterize the different lavas types in Oman. Most of the Oman ophiolite extrusive sequence is composed of lavas of composition similar to present-day MORB with the exception of slight Nb-Ta negative anomalies (V1 magmatism). V1 lavas display REE patterns and Zr/Hf ratios in the range of MORB (Zr/Hf = 33.15–38.7). In contrast, the overlaying V2 lavas, which outcrop only in the northern part of the ophiolite, are REE depleted relative to V1 and display low Zr/Hf ratios (23.6–30.5). V2 lavas may be further classified into two sub-groups. V2 type I lavas display a continuous decrease from HREE to LREE. The upper V2 type II lavas are more depleted in HREE and MREE but they are enriched in LREE. They are also distinguished by their low Nb/Ta ratios (10.53–11.65) relative to other Oman basalts (V1: 12.5–14; V2 Type I: 12.35–14.4). As for N-MORB, melting of an upwelling mantle beneath an oceanic spreading centre formed V1 lavas. V2 resulted from fluid-enhanced melting of previously depleted mantle residual after V1 extraction. This process probably occurred at different melt/rock ratios thus resulting in the two V2 sub-groups, and was enhanced in the northern part of the ophiolite. V3 lavas overlie the V1–V2 sequence in the Salahi area. They display incompatible element rich patterns (LREE > MREE > HREE) and a high Nb/Ta ratio typical of within-plate basalts. In the different studied areas, the transition from one lava type to the other seems to correlate with the block rotations revealed by paleomagnetic data.

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Theme: The Oman Ophiolite and Mid-Ocean Ridge Processes

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1. Introduction

[2] The Oman ophiolite is a sliver of the Neo-Tethys oceanic lithosphere obducted onto the Arabian plate at the end of the Cretaceous. It comprises several large structural massifs, each exposing a more or less continuous ophiolitic sequence, from the mantle section to the upper oceanic crust [see Nicolas et al., 2000, and references therein].

[3] A paleomagnetic Euler pole analysis [Perrin et al., 1994], conducted on the volcanic sequence in the Salahi area (Hilti Massif) in the central part of the ophiolite (Figure 1), has shown that the movement of this area could be modeled by a single, large rotation (about 145–150°) around an Euler pole located close to the nappe (less than 200 km away). The question was then whether these results were representative of the Hilti Massif, or of the entire ophiolite nappe. In 1999, a field campaign was carried out to complete the paleomagnetic data set in terms of geographical coverage of the ophiolite. Sampling was focused on the upper extrusive sequence, as lavas are usually better paleomagnetic recorders than intrusive or sedimentary rocks.

[4] A major and trace element study was carried out together with paleomagnetic analysis. The objectives of the geochemical study were (1) to characterize the geochemical variability of the upper extrusive sequence of the ophiolite and, (2) to evaluate possible correlations between geochemical changes and paleomagnetic rotations, in order to better understand the geodynamic environment during which block rotation occurred.

2. The Oman Ophiolite

2.1. Geological Setting

[5] The Oman ophiolite is the best-exposed piece of oceanic lithosphere at the surface of the Earth and also, one of the best-documented ophiolite, after the systematic work of several research groups (see for instance Boudier and Nicolas [1988], Coleman and Hopson [1981], Glennie et al. [1974], Lippard et al. [1986], Peters et al. [1991], and, more recently, Boudier and Juteau [2000]). It represents part of the Neo-Tethys ocean obducted onto the Arabian plate at the end of the Cretaceous (~78 Myr [Hacker et al., 1996]).

[6] The ophiolite is made up of several large (up to 4500 km²) massifs aligned along the Oman coast (Figure 1b). Each massif exposes large or more complete ophiolitic sequence, comprising a thick mantle section, gabbros and sheeted dykes topped by a 0.5–2 km thick extrusive sequence and interbedded oceanic sediments. Three magmatic sequences within the lavas constituting the extrusive section can be distinguished using petrographic and geochemical studies.

[7] The lower sequence, V1 [Beurrier, 1987; Ernewein et al., 1988] also called Geotimes by Pearce and co-workers [Alabaster et al., 1982; Lippard et al., 1986; Pearce et al., 1981] represents most of the exposed lavas (>60% [Nicolas et al., 2000]). It consists mainly of poorly vesicular brownish pillow basalts with scarce massive lava flows. Its composition is close to mid-ocean-ridge basalts -MORB- [Alabaster et al., 1982; Einaudi et al., 2000; Ernewein et al., 1988]. The eruption of V1 lavas is associated with the accretion of the Oman paleo-ridge, dated at 94–95 Ma [Hacker et al., 1996].

[8] The middle sequence outcrops mainly in the northern part of the ophiolite and represents most of the remaining lavas (>35%). It is separated from the V1 sequence by a more or less continuous layer of pelagic sediments. Three units, Lasail, Alley and clinopyroxene-phyric, were recognized by Pearce and co-workers [Alabaster et al., 1982; Lippard et al., 1986; Pearce et al., 1981] and later merged together under the same name, V2, by Beurrier [1987] and Ernewein et al. [1988]. V2 lavas are of tholeiitic affinity and are distinguished from V1 by low-Ti and low incompatible trace element contents [Beurrier et al., 1989; Ernewein et al., 1988; Lippard et al., 1986]. V2 lavas were emplaced shortly after the V1 lavas (~2 Ma [Hacker et al., 1996]). They are thought to represent either the first stages of island arc volcanism in an immature arc environment [Beurrier et al., 1989; Pearce et al., 1981], either the product of the hydrous melting of the over-ridden lithosphere during intraoceanic
The uppermost sequence, Salahi [Alabaster et al., 1982], later defined as V3 [Beurrier, 1987; Ernewein et al., 1988], is volumetrically the least significant. It has been observed only in the Salahi area in the Hilti massif, where it is separated from the lower sequences by a layer of pelagic sediments. It comprises alkaline to transitional within-plate basalts and they are thought to result from intraplate seamount volcanism, produced after the beginning of oceanic thrusting but preceding the end of the obduction of the ophiolite onto the Arabian continental margin [Ernewein et al., 1988; Lippard et al., 1986].
Hydrothermal circulations, contemporaneous with the various phases of volcanic activity, induced secondary recrystallization in the lava and interbedded sediments [Alabaster and Pearce, 1985; Pflumio, 1991].

2.2. Sampling

31 samples were selected amongst the 1999 paleomagnetic sampling: 26 cores were collected by Perrin et al. [2000] in the northern part of the ophiolite and 4 by Weiler [2000] in the Sumail massif (Figure 1, Table 1). A V3 sample from the Salahi area (Hilti massif) earlier sampled by Perrin et al. [1994] was also analyzed.

Distinction between V1 and V2 units was made according to the 1:50 000 geological maps published by the Bureau de Recherches Geologiques et Minieres [1993] and on the basis of the field criteria (sample color, flow jointing, and erosion resistance) defined by Alabaster et al. [1982]. However, the V1 and V2 volcanic units are often hardly distinguishable in the field and to find irrefutable discrimination criteria is one of the challenges of the study of the Oman ophiolite extrusive section. Even petrologic criteria, such as texture and clinopyroxene composition, are inefficient because both V1 and V2 basalts are hyalopilitic and contain identical low Ti and Na endiopside. Furthermore their groundmasses cannot be used because alteration has obliterated their original texture: both are altered to chlorite, quartz, hematite, Fe hydroxide, epidote, prehnite and zeolite. The best approach to discriminate the two series is geochemical analysis [Alabaster et al., 1982; Ernewein et al., 1988; Lippard et al., 1986; Pearce et al., 1981].

3. Results

Results are given in Table 2. Major element whole rock data were obtained by ICP-AES at the CRPG (Nancy, France). Whole rock trace element analyses were performed on a PQ2 ICP-MS (ISTEEM, Montpellier, France): Rare earth elements, Cs, Rb, Ba, Th, U, Zr, Hf and Y were determined following the method described by Ionov et al. [1992], and Nb and Ta by surrogate calibration following the procedure described in Godard et al. [2000].

3.1. Major Elements

Alteration, revealed by thin section observation, leads to substantial modifications of the primary concentrations of CaO, Na2O and K2O, and to a lesser extent, may also modify MgO and SiO2 [e.g., Ernewein et al., 1988]. Nevertheless, as shown in Figure 2, Oman lavas show variations in MgO and SiO2 correlated with TiO2, an element thought to be less affected by alteration [e.g., Winchester and Floyd, 1977]. These variations are consistent enough to be interpreted in terms of various degrees of differentiation, and reveal two differentiation trends, one for V1 lavas and the second for V2 lavas, characterized by lower TiO2 contents [Ernewein et al., 1988]. However, because of their various degrees of differentiation, both the V1 and V2 lavas display a wide range of TiO2 content and the V2 and V1 fields may overlap.

The Abdah (Sumail Massif) and Barghah (Hilti Massif) V1 samples display high TiO2 concentration (>1.1 wt.%). Because of their lower SiO2 content, the Abdad samples are thought to be less differentiated than the Barghah samples. Most lava sampled in V2 sites display low TiO2 content (<0.9 wt.%), a characteristic considered to be typical of V2 lavas. These V2 lavas appear on average less differentiated than the V1 samples in this study (lower SiO2, higher #Mg (100 × Mg/ (Mg + Fe2+))). The less differentiated V2 samples are from the western part of the Fizh massif and the most differentiated from the Sarami massif. The
other V2 sites, from the eastern part of Fizh and in Aswad, show more variable compositions. This may be an effect of alteration as noted before. However, this process cannot explain the high TiO$_2$ content (1.4–1.8 wt.%), typical of V1, in three of the Aswad samples supposed to be part of V2.

Because of alteration, major elements do not allow V3 lavas to be distinguished. The studied
samples appear slightly less differentiated than those analyzed in previous studies.

### 3.2. Trace Elements

[17] Four groups of lavas can be distinguished using trace element data (Figures 3 and 4). The first group comprises lavas sampled in V1 sites and the three high Ti Aswad samples. Their chondrite normalized Rare Earth Element (REE) patterns and contents are similar to or slightly more light REE (LREE) enriched compared to N-MORB (Figure 5). On Primitive Mantle (PM) normalized diagrams, most studied samples display moderate to strong Pb and Sr negative anomalies (also often encountered in MORB, e.g., Hofmann [1997]) and a slight Nb-Ta negative anomaly relative to neighboring elements. Note that depletions of Nb and Ta relative to La and Th are relatively unlikely to be modified by hydrothermal alteration, whereas Pb and Sr concentrations can be modified by alteration processes [e.g., Winchester and Floyd, 1977]. The studied lava compositions plot in the same field as V1 lavas analyzed in previous studies (Figure 5). They are referred to as V1 lavas following the classification proposed by Ernewein et al. [1988]. Both Abdah and Barghah lavas are trace element enriched relative to Aswad V1 samples, yet these lavas display similar TiO₂ contents. Such relatively low TiO₂ contents probably reflect late precipitation of Fe-Ti oxides and hence a higher degree of differentiation.

[18] The second and third groups of lavas were sampled in V2 sites and are referred to, respectively, as V2 type I lavas and V2 type II lavas. They are both REE depleted relative to V1 lavas (Figures 3 and 5). The V2 type I group comprises samples coming from Sarami, the eastern part of Fizh and 3 samples from Aswad. It is characterized by a steady decrease of REE content from heavy REE (HREE) to LREE on chondrite normalized diagrams (Figure 3), strong Nb-Ta negative anomalies and Pb and Sr positive anomalies relative to neighboring elements on PM normalized patterns. The samples coming from the western part of Fizh and the 3 remaining samples from Aswad form the V2 type II group. These lavas display “spoon-shaped patterns” on chondrite and PM normalized diagrams, with a strong enrichment in Th, Pb and Sr, a slight Nb and Zr negative anomaly relative to neighboring elements and low Nb/Ta ratios (Figures 3–6). Both groups plot in the same field as the previously analyzed V2 lavas (Figure 5). In the Aswad massif, where both V2 types are observed, V2 type II lavas were emplaced on top of V2 type I lavas.

[19] The V3 sample from Salahi (Hilti Massif) represents the fourth type of composition. It is characterized by a steady increase of trace element content of the most incompatible elements on chondrite and PM normalized diagrams (Figures 3 and 4).

[20] All analyzed samples display strong positive U anomalies, as well as a wide range of Cs, Rb, and Ba contents. These features mainly reflect the different secondary processes that affected the

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Table 2b. Values Obtained for BIR and BEN Standards During This Study are Compared to Those Given by Govindaraju [1994] (GSTL in Table 2b)

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*Analytical reproducibility was also assessed by analysing 3 samples twice (99 M 008-1 & 2, 99 M 100-1 & 2, and 99 M 113-1 & 2).
4. Discussion

4.1. Relationships Between Geochemistry and Paleomagnetic Orientations

This study provides the first whole rock trace element data set on the Oman extrusive section since the geochemical studies published in the 1980s [Alabaster et al., 1982; Ernewein et al., 1988; Pearce et al., 1981]. These works have shown that the Oman ophiolite extrusive sequence is formed by three consecutive magmatic sequences, distinguished by their geochemistry. This study provides improved chemical criteria, little affected by alteration and differentiation, to discriminate the different magmatic episodes: (1) V1 lavas display...
LREE/HREE and Zr/Hf ratios in the range of N-MORBs (Figures 5 and 6a). (2) V2 lavas are REE depleted relative to MORB, and display lower Zr/Hf ratios (Figure 6a). On average, they display lower TiO₂, REE and HFSE content than V1 lavas, although the two fields might overlap. V2 can be further divided into two sub-groups using ICP-MS data (Figures 6b and 6c): (3) Type I lavas display a continuous decrease from HREE to LREE and have Nb/Ta ratio similar to V1 (V1: 12.5–14; V2 Type I: 12.35–14.4). (4) Type II lavas were emplaced on top of type I lavas. They are more depleted in HREE and MREE but they are enriched in LREE. They are also distinguished by low Nb/Ta ratios (10.53–11.65) relative to other Oman lavas. (5) V3 lavas display incompatible

Figure 3. (a) V1, (b) V2 type I, (c) V2 type II and (d) V3 Rare Earth Element content normalized to Chondrite [Sun and McDonough, 1989]. Symbols are indicated in insert. The blue shaded area on Figures 3b, 3c, and 3d indicates the values obtained for V1 lavas in this study.
element rich patterns (LREE > MREE > HREE) and a high Nb/Ta ratio typical of within-plate basalts. It should be noted however that only one V3 sample was analyzed during this study.

In the Aswad massif, both V2 types are observed in areas mapped as “seamount volcanic sequences” by Alabaster et al. [1982] (i.e., where both the lower Lasail and upper Alley units where observed). On inter element diagrams, V2 type I lavas plot in the Lasail field and V2 type II lavas in the Alley field (Figure 5). However, we couldn’t establish a definite correspondence, based on lava geochemistry, between V2 type I and V2 type II lavas and the Lasail and the Alley types defined by Pearce and co-workers [Alabaster et al., 1982; Pearce et al., 1981], because (1) only new analytical techniques allow precise determination of the geochemical criteria that we use to distinguish V2 type I from V2 type II and (2) complementary analyses on clinopyroxene to determine their primary composition were precluded by alteration or absence of phenocrysts. It should be noted also that, in contrast to Alabaster et al. [1982] observations, the lower V2 type I sub-unit (Lasail?) is not limited to specific areas. Instead, it has been found throughout the northern massifs of the Oman ophiolite. In contrast, the upper V2 type II sub-unit (Alley?) has a very limited outcrop extent. Because it was difficult to ascertain unambiguously the correspondence between the lava types and sub-types revealed by our ICP-MS study and those defined by Pearce and co-workers [Alabaster et al., 1982; Pearce et al., 1981], we chose to use the classification proposed by Ernewein et al. [1988] to describe the extrusive sequence of the Oman ophiolite.

Paleomagnetic studies were carried out on the samples later analysed by ICP-MS (this study). Paleomagnetic results are summarized in Figure 8 [after Perrin et al., 2000; Perrin et al., 1994; Weiler, 2000]. For a given massif, the three main magma types (V1, V2 and V3) correspond to different paleomagnetic directions [Perrin et al., 1994]: V1 and V2 directions are statistically different but very close to each other, in agreement with the short time interval between their relative emplacement, while V3 directions are further away but in good agreement with African Late Cretaceous results when corrected for the post-Miocene opening of the Red Sea. At the scale of individual massifs within the Oman ophiolite, the V1 lavas record three significantly different paleomagnetic directions for the Aswad, Hilti-Sarami and Sumail massifs, probably indicative of tectonic rotations between these three massifs, at the time or after emplacement of the V1
lavas [Perrin et al., 2000]. Paleomagnetic data were obtained only for the V2 type I lavas. These lavas display homogeneous paleomagnetic directions, which suggest that, by the time of emplacement of the lower V2 series, the northern domain was behaving as a single tectonic unit.

4.2. Variations of Oman Extrusive Composition With Spatial Distribution and Time

[24] Both V1 and V2 lavas display HFSE/REE and HFSE/LILE fractionation, typically interpreted as the result of the contamination of their mantle source(s) by slab derived fluid-rich melts [e.g., Pearce et al., 1981; Peate and Pearce, 1998]. At each studied site, the “arc signature” increases from V1 to V2 lavas; this evolution is characterized by a decrease in the lavas HFSE/REE and HFSE/LILE ratios and an increase in LILE/REE ratios (Figure 7, Figure 8). The V2 sequence is characterized also, upward the volcanic sequence, by a decrease of, first, Zr/Hf (lower V2 Type I), then Nb/Ta ratios (upper V2 Type II). Such chemical variations are commonly attributed to arc magmatism [e.g., Peate and Pearce, 1998]. A continuous evolution in highly incompatible element fractionation is observed from the south to the north of the Oman ophiolite. The most highly incompatible element enriched are V2 type II lavas, which were only found in highly tectonized areas in the northernmost parts of the ophiolite (Fizh, Aswad). These variations can be interpreted as resulting from a stronger influence of fluid-rich melts in the northern part of the ophiolite. It should be noted

Figure 5. (a) Yb content (ppm), (b) Zr content (ppm) and (c) chondrite normalized La/Yb ratio (La/YbN) [Sun and McDonough, 1989] versus TiO\textsubscript{2} content (anhydrous wt.%) of the Oman lavas. Symbols are the same as on Figure 2 and otherwise indicated in insert.
that in spite of their differences in trace element concentrations, V1 and V2 lavas may display similar highly incompatible element ratios (e.g., Hilti V1 lavas and Sarami V2 lavas display similar Nb/Th ratios, Figure 7); this suggests small-scale heterogeneities in the mantle below the Oman paleo-ridge. They might reveal the progressive infiltration of the V1–V2 mantle source(s) by slab derived melts, and its effects on trace element enrichments.

[25] Because the “arc signature” apparently is present from the early stages of ridge accretion in Oman lavas (V1 magmatism), Pearce and co-workers [Alabaster et al., 1982; Lippard et al., 1986; Pearce et al., 1981] proposed a model in which the entire Oman ophiolite was formed in a subduction zone environment. This model is also supported by the wide range of degree of differentiation that characterizes Oman lavas, similar to that observed in subduction-related magmatism [e.g., Davidson, 1996]. In this model, the continuous increase of the “arc signature” from V1 to V2 lavas is interpreted as the transition from accretion to localized arc-type volcanism in a marginal basin close to the subduction trench [e.g., Pearce et al., 1981]. However, the structure of the ophiolite (see review in Nicolas et al. [2000]), the short time interval between V1 and V2 emplacement, and the similar “arc signatures” found in both V1 and V2 lavas are difficult to reconcile with this model. In addition, it should be noted that recent marine geological studies have shown also the lack of clear correlation of trace element signatures with location relative to subduction zones [e.g., Bach et al., 1996].

[26] In the Oman ophiolite, changes in paleomagnetic orientations and magma types are correlated along strike, suggesting a connected evolution. Boudier et al. [1997], combining paleomagnetic data and structural observations, suggested that the Oman ophiolite recorded block rotation within a “micro-plate”, and that V2 lavas were formed during associated intraoceanic thrusting. The presence of fluids in the mantle below the future Oman ophiolite may then have favored locally higher degrees of partial melting or re-melting of peridotites [e.g., Wyllie, 1981] and therefore the formation of the depleted V2 lavas. However, there are no analogues in present-day fast spreading centers for V1-type lavas overlying V2 type lavas. More recently, Moores et al. [2000] suggested that the mantle source(s) of Tethyan ophiolites (including the Oman ophiolite) had been contaminated by an ancient subduction. In this model, the “arc signature” characterizing most Oman lavas would not be representative of the regional tectonic environ-

![Figure 6.](image-url) (a) Zr/Hf versus La/YbN, (b) Nb/Ta versus Zr/Hf and (c) (La/Sm)N versus (Sm/Yb)N of the Oman lavas. Symbols are the same as on Figure 5.
ment during the Oman ophiolite formation. However, this model does not explain the observed evolution of composition of the Oman extrusives from V1 to V2 magmatism.

A better understanding of the processes controlling the lava arc signature in present-day oceanic environments should provide the means to improve our knowledge of the geodynamic environment in which the Oman ophiolite was formed.

5. Conclusion

Four groups of lavas in the Oman ophiolite can be unambiguously characterized using new ICP-MS data. The proposed classification and

Figure 7. N-MORB [Sun and McDonough, 1989] normalized (a) Ta/La, (b) Th/La, (c) Ce/Pb and (d) Zr/Sm ratios versus N-MORB normalized Nb/Th ratio for the studied lavas. Symbols are the same as on Figure 5 for the Oman lavas. They are compared to Ocean Island Basalts (OIB [Kalfoun et al., 1999]), basalts from open oceanic settings in fast spreading areas (East Pacific Rise: Pito Deep and Juan Fernandez microplate area (M. Godard and R. Hékinian, unpublished data, 1998), East Pacific seamounts [Niu and Batiza, 1997]) and from back arc basins (Lau Basin [Ewart et al., 1994], North Fiji Basin [Fleutelot, 1997]) as well as to more differentiated lavas from the Lau-Tonga arc and backarc systems [Ewart et al., 1994] and from the Izu-Bonin forearc [Murton et al., 1992].
interpretation of the different magma sequences is in agreement with previously published geochemical studies of Oman lavas. At the base of the extrusive sequence, V1 lavas were formed via a process similar to the genesis of N-MORB, by melting of an upwelling mantle beneath an oceanic spreading centre. The overlying V2 lavas probably resulted from fluid-enhanced melting of previously depleted mantle residual after V1 extraction. This process probably occurred at different melt/rock ratios, thus resulting in the two V2 sub-groups and in the various highly incompatible element signa-
tures from the north to the south of the ophiolite. The V2 type I lavas set at the base of the V2 sequence and the overlying V2 type II lavas could correspond to, respectively, the lower Lasail unit and the upper Alley unit defined by Pearce and co-workers [Alabaster et al., 1982; Pearce et al., 1981]. The third magmatic event, V3, resulted from melting of an incompatible element enriched mantle source.

[28] The three main magma types (V1, V2 and V3) correspond to different paleomagnetic directions. At the scale of the ophiolite, the V1 lavas record three significantly different paleomagnetic directions for the Aswad, Hilti-Sarami and Sumail massifs, indicating tectonic rotations between these three massifs before emplacement of V2 lavas [Perrin et al., 2000]. Incompatible elements indicate that the mantle source(s) of Oman V1–V2 lavas was progressively infiltrated by slab-derived melts, yet the variability of the “arc signature” within V1 and V2 lavas along the Oman ophiolite implies that this process did not control the V1–V2 transition. Block rotations recorded during or after V1 emplacement and the emplacement of V2 less than 2 Ma after V1 could be interpreted as being associated with a same complex accretion process, similar to that observed in “microplates” along present-day fast spreading centers.

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