Mantle xenolith-bearing Maastrichtian to Tertiary alkaline magmatism in Oman

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Mantle xenolith-bearing alkali basalts, basanites and tephrites with 1.5–2 K2O and 4–5 wt% Na2O occur as small (<100 m) plugs and dikes in the Batain and Haushi-Huqf areas, and WNW of Muscat. Their black color and the common presence of peridotite xenoliths allow a separation from older alkaline rocks and from the ophiolitic extrusive rocks. Two main dike directions, approximately E-W and N-S oriented, are observed. Intrusions seem to occur where these two fault systems intersect. The basalts crosscut the Upper Maastrichtian siliciclastic rocks of the Fayah Formation and the nappe stack of the Eastern Ophiolite Belt of the Batain area. They have not been observed intruding the Tertiary shallow marine carbonates although K-Ar whole rock dating on these lavas yielded Late Eocene 37 ± 1 to 44 ± 1 Ma ages. The rocks are aphyric and fine-grained with microgranular, and less common microtrachytic texture. They contain magmatic olivine (Fo80–82), nepheline (Ne82–86Ks14–18), clinopyroxene (Di46En25Wo28) with 2.5 wt% Al2O3, accessory phlogopite (X_Mg 0.6, with 5.5 wt% TiO2), in a microcrystalline or glassy matrix. Plagioclase is only observed in few samples. Locally occurring mm to cm-sized immiscible leucocratic melt droplets consist of potassium feldspar (An1–4Ab37–39Or60–70), plagioclase (An20–22Ab65Or13–15), nepheline (Ne85Ks15), phlogopite (X_Mg 0.8, with ~6–7 wt% TiO2), and titanomagnetite with ~8 wt% TiO2. More than 95% of the xenoliths are <5cm-sized weakly to clearly foliated spinel peridotites of mantle origin. Sedimentary xenoliths (hornfelses) are rare and lower crustal xenoliths were not found. The peridotite xenoliths consist of olivine (Fo90–92), enstatite (En93Fs9Wo8) with 3.1–3.3 wt% Al2O3, diopside (Di42En26Wo32) with 3–6 wt% Al2O3, and Cr-spinel with ~60 mol% spinel, 20% h㇐ercynite, and 15–16% magnesiocromite. The age, chemical composition, and structural position suggest a relation with local tectonic movements associated with plate reorganization in the Owens Basin region prior to the Red Sea opening.

Components: 6840 words, 4 figures, 3 tables.

Keywords: Oman; chemistry; mineralogy; volcanic rocks; Indian Ocean; extensional tectonics.

Index Terms: 1099 Geochemistry: General or miscellaneous; 3040 Marine Geology and Geophysics: Plate tectonics (8150, 8155, 8157, 8158); 3625 Mineralogy and Petrology: Descriptive mineralogy; 9699 Information Related to Geologic Time: General or miscellaneous.

Received 17 October 2001; Revised 13 June 2002; Accepted 18 June 2003; Published 24 September 2003.


Theme: The Oman Ophiolite and Mid-Ocean Ridge Processes

Guest Editors: Peter Kelemen, Chris MacLeod, and Susumu Umino

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1. Introduction

Intracontinental alkaline volcanism occurs mainly in association with extensional tectonic regimes (e.g., Red Sea rifting) although transpressional tectonic settings are known [e.g., Glazner and Bartley, 1994]. In Oman alkaline volcanism in a continental setting occurred in association with the Permian-Triassic rifting and opening of the Neo-Tethys [e.g., Glennie et al., 1974]. A contractual regime lasted from the Cenomanian to the end of Cretaceous resulting in thrusting of the Semail Ophiolite-Hawasina nappes complex in Campanian [e.g., Glennie et al., 1974], and subsequently thrusting of the Eastern Ophiolite Belt (Batain nappes, Masirah ophiolites, Ras Madrekarah and Ras Jibschi) at the Cretaceous-Tertiary boundary [e.g., Gnos et al., 1997; Peters et al., 2001]. Extension associated with reorganization of the plates after obduction of the Semail Ophiolite started at the end of the Maastrichtian [Wyns et al., 1992a] thus coeval with the thrusting of the Eastern Ophiolite Belt. Associated tectonic movements gave way to eruption of alkaline olivine basalt (with olivine xenocrysts?) producing flows, pillow lavas and volcanoclastic units. This late Maastrichtian volcanism is preserved in the terrestrial to marine Qahlah Formation [Glennie et al., 1974; Wyns et al., 1992b] of the Sur area.

In the Haushi-Huqf area alkali basalts containing xenoliths derived from the Precambrian sedimentary strata and the underlying metamorphic and igneous Precambrian basement but not from the mantle were described by Dubreuilh et al. [1992a, 1992b]. These rocks, originally assumed to be Tertiary in age were subsequently recognized to be Ordovician in age [Oterdoom et al., 1999]. However, the authors locate and describe in the same paper 20–30 km to the south other basalt intrusions which they interpret as Tertiary in age. WSW of Muscat, Al-Harthy et al. [1991] found alkali olivine basalts at Rusayl containing xenocrysts and small xenoliths of mantle origin. Mantle xenolith bearing alkali olivine basalts are also common in the Batain area [e.g., Shackleton et al., 1990] located at the eastern end of the Oman Mountains (Figure 1). In this paper we will address the mantle-xenolith bearing alkali olivine basalt outcrops of the Batain region in the southern Oman Mountains (Figure 1) and compare them with the occurrence at Rusayl in the central Oman Mountains recognized by Al-Harthy et al. [1991].

2. Geologic Setting

Glennie et al. [1974] recognized the allochthonous origin of the Batain sedimentary rocks and mapped them as Wahrah and Ibra Formations (Hawasina nappes) on their 1:500’000 scale map. Shackleton et al. [1990] published a more detailed map of the region describing several outcrops of black volcanic rocks as Tertiary, and referring to 37–44 Ma whole rock K-Ar ages obtained by A. C. Ries et al. (A continuation of geological studies in the Batain Coast Region, NE Oman, unpublished report, Amoco Petroleum Company, 1985). Geological maps, sheets Sur and Al Ashkharah at 1:250’000 scale, accompanied by explanatory notes were published by Wyns et al. [1992a, 1992b], Bèchennec et al. [1992] and Le Métour et al. [1992]. On these maps additional localities of Tertiary volcanics are indicated. Only recently it was recognized that the Batain area to the east of the Jebel Ja’alan crystalline basement outcrops (Figure 1) is not part of the Semail Ophiolite-Hawasina nappe complex. The rocks of this area belong to a discontinuous Eastern Ophiolite Belt which was thrust onto the Arabian continent only at the Cretaceous/Tertiary boundary, thus 20 Ma after the Semail ophiolite obuction [Gnos and Perrin, 1995; Gnos et al., 1997; Schreurs and Immenhauser, 1999; Immenhauser et al., 2000]. These new ideas led to a detailed mapping of Shackleton et al.’s [1990] melange [Immenhauser et al., 1998; Hauser, 2000; Moser, 2000; Peters et al., 2001], the recognition of a set of coherent sedimentary nappes forming the bulk of the Batain area, and a proper stratigraphic definition of the units present (Figure 1).

Filbrandt et al. [1991] and Wyns et al. [1992a] discussed the Late Cretaceous to early Tertiary syn-sedimentary tectonic movements of the Jebel Ja’alan-Batain area. They recognized that detritus derived from the Hawasina nappes northwest and west of the Jebel Ja’alan formed alluvial fans...
Figure 1. Geologic map of the Batain area, SE Oman, based on Hauser [2000]. Early Tertiary alkali basalt dikes and small intrusion [Le Métour et al., 1992; Peters et al., 2001, and own data] are marked with black stars. Numbers refer to localities discussed in the text.
during the end of Campanian to Maastrichtian [Filbrandt et al., 1991]. Later in Maastrichtian the terrigenous input ceased and a shallow carbonate shelf established. Tectonic activity increased during the end-Maastrichtian/Paleocene causing reactivation of faults and uplift of the Jebel Ja’alan [Filbrandt et al., 1991; Würsten et al., 1991]. The main fault sets created or reactivated are oriented N-S to NNE-SSW (parallel to the trend of the Haushi-Huqf -Jebel Ja’alan horst) and E-W to ENE-WSW (for example northern edge of Jebel Ja’alan). The alkali basalt magma hence forms east or north trending dikes. Small plugs and intrusions seem to occur at intersections of the two faults sets. The intrusion may produce small thermal aureoles in the surrounding sedimentary rocks, as for example at Jebel Fayah. In the Batain area the intrusions crosscut sedimentary rocks of the Batain nappes [Peters et al., 2001] and the Fayah Formation [Shackleton et al., 1990] but were not observed in Eocene rocks. The same stratigraphic relationship was also recognised by Al-Harthy et al. [1991] in the central Oman Mountains where the basalts intrude the Paleocene Jafnayn Formation but not the Eocene strata. All know occurrences of such basalts in the Batain area are indicated in Figure 1 and additional sample localities are marked on the overview map.

3. Rock Description

[6] The alkali basalts form black dikes and plugs, sometimes with glassy appearance, and are easily recognized in the field. In most cases the lavas are aphyric containing only angular fragments of olivine xenocrysts and/or cm-sized mantle xenoliths. The basalts form small intrusions (Figure 2a) or dm to m-sized dikes (Figure 2b). Columnar jointing is locally observed at the contact to the wall rocks, and small thermal aureoles can be present. With few exceptions the dikes and intrusions contain 0.5–5 cm sized mantle xenoliths and xenocrysts, which can make up a few percents of the rock volume. Xenoliths from the Batain sedimentary nappes are also locally common and include red or green cherts, pale limestones and quartz-rich lithologies. Xenoliths of Precambrian sedimentary or crystalline basement rocks as described from the Haushi-Huqf area to the south [Dubreuil et al., 1992a, 1992b] were not observed in the Batain region. Flows and pillow lavas were found at one locality (44; Figure 1) in the Batain region. Unlike the Mesozoic pillow lavas of the Batain thrust complex the pillow lavas belonging to the late Cretaceous/Tertiary magmatism are relatively fresh. They are ophitic to porphyritic (nepheline and pyroxene) in texture, locally amygdaloidal, and weather brownish. At Jebel Fayah white, mm to cm-sized droplets of a leucocratic magma can be observed in the dark basalt (Figure 2c). Similarly leucocratic cm-sized, irregular-shaped melt droplets occur also in the basalt intrusion at Rusayl. The isolated outcrop in the Wahiba Sands (Figures 1 and 2a) is especially rich in mantle xenoliths (Figure 2c). The basalt intrusion at Jebel Fayah (type locality of the Fayah Formation) [Shackleton et al., 1990] is well accessible and shows most of the phenomena described above. For a description of the outcrops near the Sultan Qaboos University in the central Oman Mountains readers are referred to Al-Harthy et al. [1990].

[7] In thin section the basalts show porphyric microgranular texture (Figure 3a) containing euhedral olivine phenocrysts that are partly resorbed, subhedral to euhedral light brownish clinopyroxene (Figure 3a), nepheline laths (Figure 3b), locally plagioclase, and squares of titanomagnetite. Only at Rusayl (64) some clinopyroxene rims show the anomalous colors under crossed polarizers characteristic of Ti-augite. The groundmass consists of nepheline, potassium and calcic feldspar, clinopyroxene, glass (mainly devitrified), and locally abundant phlogopite (Figure 3c). Clinopyroxene may be slightly zoned and commonly contains small inclu- sions in the rim regions. Phlogopite shows dark rims, probably caused by formation of oxides due to oxidation. The nepheline crystals may display a strong alignment producing a microtrachytic texture. The leucocratic phonolitic melt droplets found at Jebel Fayah (Figure 2c) and Rusayl consist of potassium feldspar, nepheline, plagioclase, phlogopite and Ti-magnetite (Figure 3c). The xenoliths are medium-grained with equigranular textures (Figure 3d), and display weak to clear foliation. All xenoliths investigated are spinel-bearing and have
lherzolitic or harzburgitic mineralogy. In thin section the spinels are brown transparent and the pyroxenes are without exsolution lamellae. The olivine may contain few, wide-standing dislocation walls.

Many xenoliths show trails of melt inclusions (healed cracks). Locally melt infiltrating along grain boundaries causes incipient xenolith desintegration. Along such grain boundaries growth of small magmatic olivine and clinopyroxene is observed, and relic glass is found. Whereas the Batain dikes and intrusion contain generally only small amounts of mainly devitrified glass, the original glass content in rocks from the Rusayl locality [Al-Harthy et al., 1991] is much higher and may reach 20% (Figure 3d). Some samples from the later locality are clinopyroxene-rich with crystals reaching cm-size. A thin section of a 5 mm
wide small contact aureole developed in Triassic silicified marly limestone (locality 59) contains 0.1–0.2 mm sized zoned grossularite garnets with a lemon core, colorless rim and anisotropic optical character. Associated with it occur optically anomalous zoisite, calcite, and wollastonite or scapolite.

4. Rock and Mineral Chemistry

4.1. Rock Chemistry

[6] Only rock material free of macroscopically visible xenocrysts was used. Major and trace element concentrations were analyzed by XRF at the Fribourg/Bern facility. Fe\(^{2+}\)/Fe\(^{3+}\) concentrations were determined colorimetrically using the bipyridine method, and the H\(_2\)O content of the samples was analyzed with the Penfield method. Analyses are listed in Table 1. Most analyses fall in the basanite field with >10% normative olivine (Table 1; Figure 4) in the TAS diagram [LeMaitre et al., 1989]. All rocks are nepheline normative (Table 1), and in many of the rocks nepheline is also recognizable in thin section. The two analyses from the Rusayl locality (OE64) show the lowest Na\(_2\)O + K\(_2\)O contents, and the highest Ba, Sr and
Table 1. Whole Rock and Trace Element Data for Tertiary Alkali Basalts

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<tr>
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<th>Rusayl</th>
<th>Wahiba Sands</th>
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**Given in wt%**

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**Given in ppm**

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*Ab, below detection; Wo, En and Fs are normative pyroxene end-members, Fo, Fa and Cs (larnite) normative olivine end-members."
Ni concentrations. The Ni-content in the xenolith-free pillow lavas (44) is at detection limit. The trace element patterns are characteristic for within plate alkali basalts. Although no chemical analysis is available from the leucocratic melt, based on its mineral chemistry (see discussion below) it is enriched in K, Na and Si, and with higher Fe/Mg ratio if compared with the basalt. In general the rock chemistry is comparable to the Maastrichtian volcanic rocks of the Qalhah Formation [Wyns et al., 1992a; OE62 in Table 1] where they were described as alkali-rich, SiO₂-poor basalts with strong enrichment in light REE’s.

4.2. Mineral Chemistry

Magmatic and xenolith minerals were analyzed on a Cameca SX-50 microprobe using beam conditions of 15 kV and 20 nA, wavelength dispersive spectrometers, natural and synthetic silicate or oxide standards, a spot size of 2–10 μm, and element peak and background measurement times of 20 s.

The brownish magmatic pyroxene in the basaltic rocks and in the leucocratic melt droplets at Jebel Fayah (OE42; Table 2) is an aluminian ferroan diopside [Morimoto et al., 1988] containing 0.06–0.07 Ti pfu, 2.2–2.6 wt% TiO₂ and 6–7 wt% Al₂O₃. The ferric iron (and aegirine) content of the diopside in the phonolitic blebs is twice as high (Table 2). The Ti-content in clinopyroxene is generally too low to develop the anomalous color characteristic for titanian augite. Clinopyroxene xenocrysts or clinopyroxene in the xenoliths is an aluminian diopside, clearly distinguishable from magmatic clinopyroxene by its lower aluminium (3.0–3.5 wt%) and titanium contents (Tables 2 and 3). Sanidine has a composition of Abₐ₀.₃₇₋ₐ₀.₄₃An₀.₃₇₋ₐ₀.⁴₉Or₀.₅₇₋ₐ₀.₆₉ and plagioclase is typically Abₐ₄₋ₐ₅An₄₋ₐ₅Or₁₋ₐ₂ (Tables 2 and 3). In the leucocratic melt droplets at Jebel Fayah plagioclase has a composition of Abₐ₆₋ₐ₇Anₐ₂₋ₐ₃Or₁₋ₐ₂. Nepheline in this droplets and in the matrix shows a compositional range of Ne₁₈₋ₐ₂₆K₁₄₋ₐ₁₈ (Tables 2 and 3). Magmatic olivine seems relatively rare but was analyzed in sample OE67 (Table 3) where it showed a composition of Fo₈₁₋₈₂ (Table 3). This chemical composition allows a clear distinction from olivine xenocrysts (Fo₉₀₋₉₂) present in nearly all samples (Tables 2 and 3).

Accessory phlogopite (Xₐ₉₅₀.₆, with 5.5 wt% TiO₂) is present in some samples and shows generally strong oxidation (oxyphlogopite). Larger phlogopite crystals with similar composition occur in the phonolitic blebs at Jebel Fayah (Figure 3c; Table 2). The mineral chemistry of the basalts from the Rusayl locality (OE 64) described by Al-Harthy...
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**Table 2.** Representative Magmatic and Xenolithic Mineral Compositions in Jebel Fayah Intrusion 42

- **Mag**: Magmatic
- **Exs**: Exsolutions
- **Xen**: Xenolithic

*aCalculated value; mag, magmatic; xen, xenolithic; exs, leucocratic exsolutions.*
Table 3. Representative Magmatic and Xenolithic Mineral Compositions in samples 64 (Rusayl) and 67 (Wahiba Sands)

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*Calculated value; mag, magmatic; xen, xenolithic.
et al. [1991] is also very similar and representative analyses are listed in Table 3.

The peridotite xenoliths consist of olivine (Fo90-92), enstatite (En89Fs09Wo29) with 3.1–3.3 wt% Al2O3, diopside (Di45En26Wo29) with 3–6 wt% Al2O3, and brownish-red transparent Cr-spinel with /C24 60 mol% spinel, 20% hercynite, and 15–16% magnesiochromite (Tables 2 and 3). At the xenolith rims melt infiltrated along olivine rims which produced opaque ulvöspinel with ca. 20 mol% magnesioferrite and 25% magnetite components. This ulvospinel is surrounded by tiny newly grown olivine grains.

5. Discussion

Immiscibility in alkaline magmas was, for example, discussed by Philpotts [1976]. The leucocratic (phonolitic) melt droplets observed in mafic alkaline magma at Jebel Fayah and at Rusayl suggest immiscibility. The whole rock chemistry of the primary basaltic magma and estimates for the leucocratic magma based on the analyzed mineral compositions suggest that the observed compositions probably plot on the two sides of a two-liquid field [Roedder, 1951; Philpotts, 1982]. Whereas at Jebel Fayah liquid immiscibility seems to be frozen in an early stage (small and mainly round leucocratic droplets), droplets seem to have coalesced at Rusayl to form 5 cm large irregular patches.

The alkaline volcanic rocks of the Qahlah Formation are Maastrichtian-Paleocene in age [Glennie et al., 1974; Wyns et al., 1992a]. The alkali olivine basalts of the Haushi-Huqf area [Oterdoom et al., 1999] may belong to the same volcanism, because they occur in vicinity of the same fault zone, or they may be related to the younger Eocene stage. The pillow lavas of the Al Askharah region may also belong to the early or the Eocene alkaline magmatism. The location of these volcanic rocks points to an association with the horst and graben tectonics which lifted the Haushi-Huqf and the Jebel Ja’alan areas up relative to the surrounding terrain [Filbrandt et al., 1991; Würsten et al., 1991; Wyns et al., 1992a]. This movements also caused synsedimentary deforma-
Arabian continental margin along which the alkaline melts intruded.

[17] The presence of spinel-bearing mantle xenoliths in the Oman case indicates that brittle deformation reached upper mantle levels (ca. 50 km) and the Al-content of xenolith orthopyroxene suggests upper mantle equilibrium temperatures of \( \sim 950^\circ \text{C} \).

Acknowledgments

[18] Hilal Al-Azri, Director General of Mineral Resources, Ministry of Commerce and Industry, Sultanate of Oman is thanked for providing logistic help. Ruth Mäder provided FeO and \( \text{H}_2\text{O}^+ \) determinations. EMP work was made possible by the Swiss National Fonds grant 21-26579.89. J. W. Shervais and two anonymous persons are thanked for their reviews.

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