

Magmatic evolution of the Jbel Boho alkaline complex in the Bou Azzer inlier (Anti-Atlas/Morocco) and its relation to REE mineralization



Rachid Benaouda^{a, b, *}, Astrid Holzheid^a, Volker Schenk^{a, c}, Lakhli Badra^d, Aomar Ennaciri^e

^a Institut für Geowissenschaften, Universität Kiel, 24118 Kiel, Germany

^b GEOMAR, Helmholtz Centre for Ocean Research, 24148 Kiel, Germany

^c Institut für Geowissenschaften, Universität Heidelberg, Im Neuenheimer Feld 236, 69120 Heidelberg, Germany

^d Faculté des sciences, Université My Ismail, Meknes, Morocco

^e Managem Group, Marrakech, Morocco

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ABSTRACT

The Jbel Boho complex (Anti-Atlas/Morocco) is an alkaline magmatic complex that was formed during the Precambrian-Cambrian transition, contemporaneous with the lower early Cambrian dolomite sequence. The complex consists of a volcanic sequence comprising basanites, trachyandesites, trachytes and rhyolites that is intruded by a syenitic pluton. Both the volcanic suite and the pluton are cut by later microsyenitic and rhyolitic dykes.

Although all Jbel Boho magmas were probably ultimately derived from the same, intraplate or plume-like source, new geochemical evidence supports the concept of a minimum three principal magma generations having formed the complex. Whereas all volcanic rocks (first generation) are LREE enriched and appear to be formed by fractional crystallization of a mantle-derived magma, resulting in strong negative Eu anomalies in the more evolved rocks associated with low Zr/Hf and Nb/Ta values, the younger syenitic pluton displays almost no negative Eu anomaly and very high Zr/Hf and Nb/Ta. The syenite is considered to be formed by a second generation of melt and likely formed through partial melting of underplated mafic rocks. The syenitic pluton consists of two types of syenitic rocks; olivine syenite and quartz syenite. The presence of quartz and a strong positive Pb anomaly in the quartz syenite contrasts strongly with the negative Pb anomaly in the olivine syenite and suggests the latter results from crustal contamination of the former. The late dyke swarm (third generation of melt) comprises microsyenitic and subalkaline rhyolitic compositions. The strong decrease of the alkali elements, Zr/Hf and Nb/Ta and the high SiO₂ contents in the rhyolitic dykes might be the result of mineral fractionation and addition of mineralizing fluids, allowing inter-element fractionation of even highly incompatible HFSE due to the presence of fluorine. The occurrence of fluorite in some volcanic rocks and the Ca-REE-F carbonate mineral synchysite in the dykes with very high LREE contents (Ce ~720 ppm found in one rhyolitic dyke) suggest the fluorine-rich nature of this system and the role played by addition of mineralizing fluids.

The REE mineralization expressed as synchysite-(Ce) is detected in a subalkaline rhyolitic dyke (with Σ LREE = 1750 ppm) associated with quartz, chlorite and occasionally with Fe-oxides. The synchysite mineralization is probably the result of REE transport by acidic hydrothermal fluids as chloride complex and their neutralization during fluid-rock interaction.

The major tectonic change from compressive to extensional regime in the late Neoproterozoic induced the emplacement of voluminous volcanoclastic series of the Ediacran Ouarzazate Group. The alkaline, within-plate nature of the Jbel Boho igneous complex implies that this extensional setting continued during the early Cambrian.

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* Corresponding author. GEOMAR, Helmholtz Centre for Ocean Research, 24148 Kiel, Germany.
E-mail address: rbenaouda@geomar.de (R. Benaouda).

1. Introduction

Rare earth element (REE) deposits are commonly associated with alkaline magmatic rocks. Economically relevant concentrations of REE in alkaline rocks most likely originate from both fractional crystallization of primary mantle melts and hydrothermal activities coupled with chloride-rich fluid immiscibility could lead to the formation of evolved rocks with high REE contents (Chakhmouradian and Zaitsev, 2012; Williams-Jones et al., 2012). Understanding the magmatic evolution of alkaline magmatic complexes may therefore provide basic information to allow better identification, during prospection, of those rocks of a complex that may contain elevated REE concentrations.

Deposits of economic importance are, for example, the syenite-hosted loparite deposits (loparite: $(\text{Ca}, \text{La}, \text{Na}, \text{Ca}, \text{Sr})(\text{Ti}, \text{Nb})\text{O}_3$) in the Khibiny and Lovozero complex in the Kola peninsula, Russia, (~30,000 tonnes of ore with 34 wt% rare earth oxides (REO)), the syenite-hosted eudialyte (eudialyte sensu stricto: $\text{Na}_{15}\text{Ca}_6\text{Fe}_3\text{Zr}_3\text{Si}[1](\text{Si}_{25}\text{O}_{73})(\text{O}, \text{OH}, \text{H}_2\text{O})_3(\text{Cl}, \text{OH})_2$) with the major part of the REE and Nb substituting Ca and Si[1]) in the Ilimaussaq alkaline complex in Greenland (~2 million tonnes with 1.5 wt% REO), and the Thor Lake syenite- and alkaline granite-hosted REE deposit in south-western Canada that contain about 65.6 million tonnes of ore with 2.53 wt% REO in monazite, allanite and REE-F-carbonate minerals (Orris and Grauch, 2002; Salvi and Williams-Jones, 2005).

Alkaline rocks are relatively rare on Earth (ca 1 vol% of all igneous rocks) and, although the majority of them occur in extensional geodynamic settings (e.g. in the East African rift system in Kenya; Baker (1987)), they can also form in other geodynamic settings, namely in compressive regimes like the Tamazert alkaline complex in the central High Atlas of Morocco (Bouabdellah et al., 2010) or even in the oceanic crust with relation to hotspot

volcanism as exposed on Maio of the Cape Verde Islands (Le Bas, 1987).

Several alkaline provinces occur in Morocco: Oujda, Taourirt, Rekkam, Azrou and Oulmes in the Middle Atlas and the Tamazert complex in the High Atlas, which are of Tertiary ages, whereas the early Cambrian Jbel Boho, Saghro and Siroua complexes are situated in the Anti Atlas. Until recently only the Tamazert alkaline complex in the central High Atlas (Fig. 1) was known for REE mineralization e.g., monazite, parisite and synchysite (Bouabdellah et al., 2010; Mourtada, 1997; Woolley, 2001). Recently the Government's ONHYM (National Office for Hydrocarbon and Mines) published new exploration data with very promising Fe–Nb–REE concentrations in the region of Ouled Dlim south of Morocco (Moroccan Mauritanides) (Fig. 1). The Ouled Dlim complex consists of Fe-carbonatite including three intrusions emplaced along the western margin of the Archean Reguibat Shield. The results show generally very high REE contents up to 3 wt% (Mouttaqi et al., 2011; ONHYM, 2015, 2013; Qalbi et al., 2011; Zerdane et al., 2011). In addition, this study reports the occurrence of REE mineralization in the late rhyolitic dykes in the Jbel Boho alkaline complex. Leblanc (1971) already assumed a possible REE enrichment in the later alkaline intrusive dykes of Jbel Boho without testing this hypothesis by geochemical studies.

The Jbel Boho in the Bou Azzer inlier (Anti-Atlas) (Figs. 1 and 2) is a magmatic complex that was first described by Choubert (1952) and later by Leblanc (1981a, 1971). The alkaline nature of the Jbel Boho complex was first reported by Gasquet et al. (2005), Álvaro et al. (2006) and is confirmed by the present work.

The aim of the present study is to decipher in more detail the magmatic evolution of the Jbel Boho complex from primary to evolved rocks and the possible relationship of this evolution to the REE mineralization. We identify for the first time the occurrence of

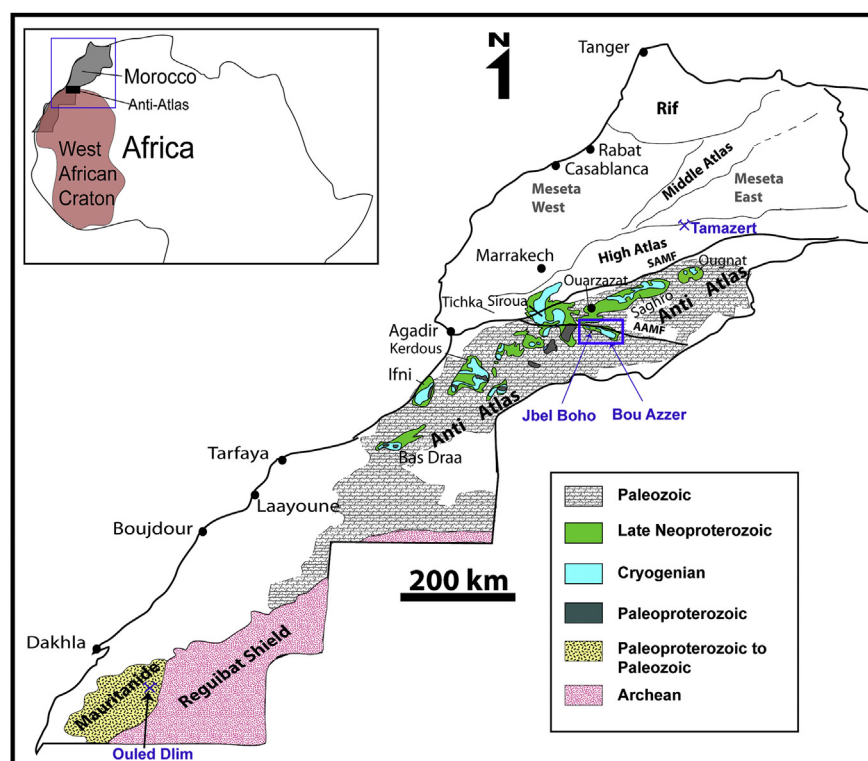


Fig. 1. Geological map of the Moroccan Anti-Atlas showing schematically the major geological domains of Morocco (Rif, Meseta East and West, as well as Middle and High Atlas) with the Jbel Boho complex within the Bou Azzer inlier in the Anti-Atlas. The approximate location of the Tamazert alkaline complex in the High Atlas, the location of the REE carbonatite complex of Ouled Dlim in the Mauritanide and the names of cities and other locations are added for orientation. Map modified after Gasquet et al. (2005) and Mouttaqi et al. (2011).

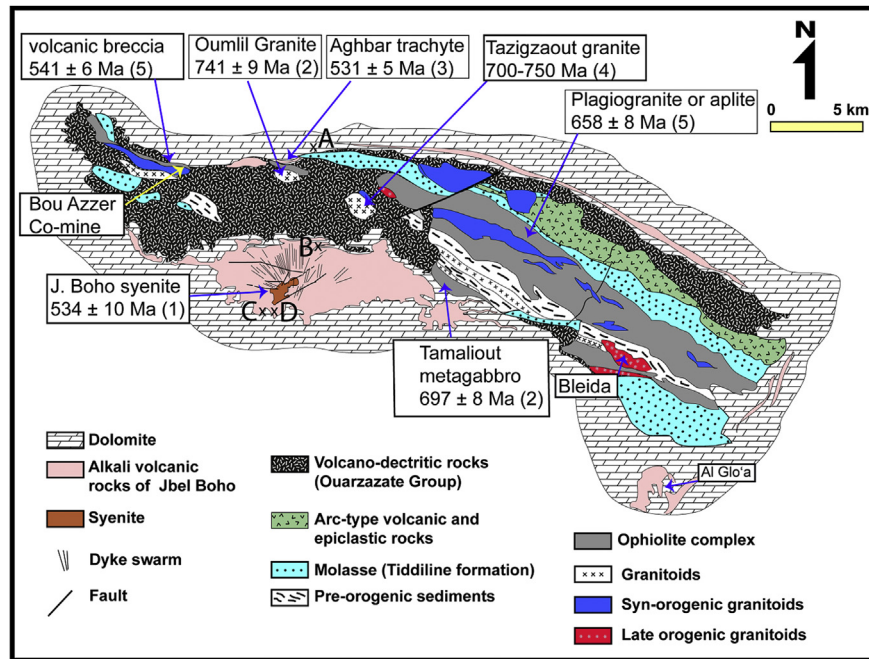


Fig. 2. Simplified geological map of the Bou Azzer and Jbel Boho with isotopic ages. Map modified after Leblanc (Leblanc, 1981a). Isotopic data from U–Pb zircon: (1) (Ducrot and Lancelot, 1977), (2) (El Hadi et al., 2010), (3) (Gasquet et al., 2005), (4) (D'Lemos et al., 2006), (5) (Blein et al., 2014). For A, B, C, D designations see Fig. 3.

two types of syenites (olivine and quartz syenite) and subalkaline rhyolitic dykes in the Jbel Boho complex as well as the occurrence of the Ca-REE-F-carbonate mineral synchysite in the LREE-enriched dyke.

In addition we describe the mineralogy of the different rocks, the mineral assemblage of the syenitic pluton and the chemistry of the REE hosting mineral synchysite-(Ce) in the LREE-enriched dyke.

2. Geologic setting

The Moroccan Anti-Atlas is located south of the High Atlas and is separated from it by the South Atlas Major Fault (SAMF; Fig. 1). It is a large area of Precambrian rock-units exposed in several Proterozoic erosional windows that display the NE-SW oriented Pan-African structures along the northern boundary of the Paleoproterozoic West African Craton (WAC) (Choubert, 1952; Leblanc, 1981a, 1981b). The Jbel Boho complex is part of the Bou Azzer inlier, which is situated in the Central Anti-Atlas along the Anti Atlas Major Fault (AAMF, Fig. 1). It is well-known for its Precambrian ophiolite with economically important cobalt mines (Leblanc, 1981a, 1981b, 1972). Since the discovery of this ophiolite complex, various Pan-African geodynamic settings have been proposed for its emplacement: Subduction zone setting with the subduction of the oceanic lithosphere towards the south (Gasquet et al., 2005; Leblanc and Lancelot, 1980; Leblanc and Moussine-Pouchkine, 1994), or towards the north (Bousquet et al., 2008; El Hadi et al., 2010; Naidoo et al., 1991; Saquaque et al., 1989; Soulaïmani et al., 2006). Geophysical magnetic studies support the hypothesis of the north dipping subduction zone (Soulaïmani et al., 2006). The location of the Bou Azzer ophiolite and the outcrops of the Eburnean basement restricted to the south of the AAMF led some authors to consider this fracture as the suture along the northern boundary of the WAC (Bouougri, 2003; Bousquet et al., 2008; El Hadi et al., 2010; Hefferan et al., 2000; Leblanc, 1981b; Saquaque et al., 1989; Soulaïmani et al., 2003), but other authors suggest that the so-called AAMF represent in fact an intracratonic aulacogen and the Bou Azzer ophiolite could be an allochthonous unit deriving from the north of the SAMF that

might represent the northern boundary of the WAC (Ennih and Liégeois, 2008, 2003, 2001; Gasquet et al., 2008). However the above-mentioned geophysical magnetic study supports the interpretation that the AAMF represents the suture along the northern boundary of the WAC.

Prior to 2006 the granitoids of Tazigzaout and Oumilil in Bou Azzer were considered to belong to the Paleoproterozoic basement. As summarized on the simplified geological map of the Bou Azzer inlier (Fig. 2), new geochronological data (U–Pb zircon dating) indicate Neoproterozoic ages for “augen granite gneiss” at Tazigzaout (750–700 Ma, D'Lemos et al. (2006)) and for the Oumilil granite (741 ± 9 Ma) as well as for the ophiolitic Tamaliout metagabbro (697 ± 8 Ma, El Hadi et al. (2010)) and for an ophiolitic plagiogranite or aplite (658 ± 8 Ma, Blein et al. (2014)). The Bou Azzer inlier therefore consists of several Neoproterozoic units that evolved prior to and during the emplacement of the ophiolite. Fig. 2 also shows the U–Pb zircon ages from the much younger Jbel Boho syenite (534 ± 10 Ma, Ducrot and Lancelot (1977)), the Aghbar trachytic sills (531 ± 5 Ma Gasquet et al. (2005)) and a porphyric basalt (541 ± 6 Ma Blein et al. (2014)) in the Bou Azzer mine area related to the base of the Early Cambrian.

After the compressive phase of the Pan-African orogeny and the Bou Azzer ophiolite emplacement calc-alkaline magmatism started and interpreted to be related to an extensional tectonic regime (Ezzouhairi et al., 2008; Gasquet et al., 2005; Thomas et al., 2004). The related volcano-clastic rocks are part of the Ouarzazate Group (580–550 Ma, up to ~2 km thick), which has been described in more detail by e.g. Gasquet et al. (2008, 2005) and Thomas et al. (2004, 2002).

Following this magmatic stage, early Cambrian carbonates and red sandstone of the Lie-de-vin series (Taliwine formation) were deposited on an epicontinental platform, which is attributed to a marine transgression along the northern edge of the WAC (Algouti et al., 2001; Piqué et al., 1999). The Jbel Boho alkaline complex was emplaced during this time under subaerial to shallow-water conditions as indicated by the intercalation of Jbel Boho volcanic rocks with the lower early Cambrian dolomites. The Lie-de-vin series and

the early Cambrian upper dolomites (Igoudine formation) overlie the Jbel Boho volcanic rocks (Alvaro et al., 2006; Choubert, 1952; Leblanc, 1981a). Intercalations between alkaline volcanic rocks and the early Cambrian dolomites are also found in the Al Glo'a area south east of the Bou Azzer inlier (Fig. 2). From a lithostratigraphic point of view the Al Gloa volcano-sedimentary rocks are directly linked to the Jbel Boho formation.

The relationship of the early Cambrian dolomite and the Lie-de-vin series with the Jbel Boho volcanic rocks is well exposed in the

field. Fig. 3 A–D show the intercalations of the lower dolomites with the volcanic rocks (Fig. 3A and B), the overlying upper dolomites of the Igoudine formation (Fig. 3C) and the intercalation of the upper dolomites with the Lie-de-vin series (Fig. 3D). Fig. 4 summarizes the stratigraphic sequence of the outcropping Bou Azzer units including the Jbel Boho complex.

As the main emphasis of the present study was on the magmatic evolution of the Jbel Boho alkaline complex, the regional geology of Bou Azzer is not described in detail. More information regarding

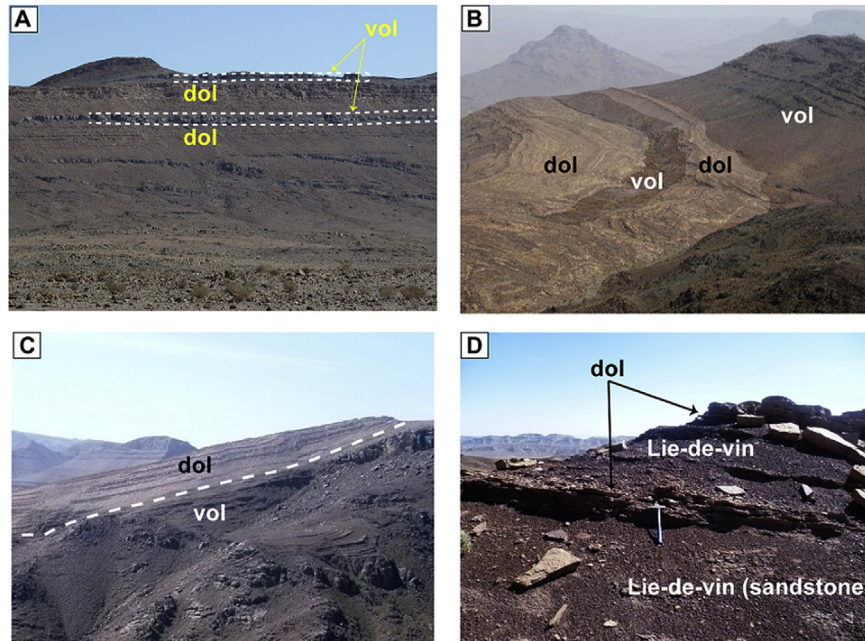


Fig. 3. Intercalations of Jbel Boho volcanic rocks between the early Cambrian dolomites north of Jbel Boho near Aghbar. A - view toward north; B - view toward east between the Ouarzazate formation and the Jbel Boho volcanic rocks; C - view toward west with the upper dolomite of the Igoudine formation covering volcanic rocks south of Jbel Boho, D - view toward east revealing the upper dolomite and the Lie-de-vin series (Taliwine formation) south of Jbel Boho. vol: volcanic rocks, dol: dolomite.

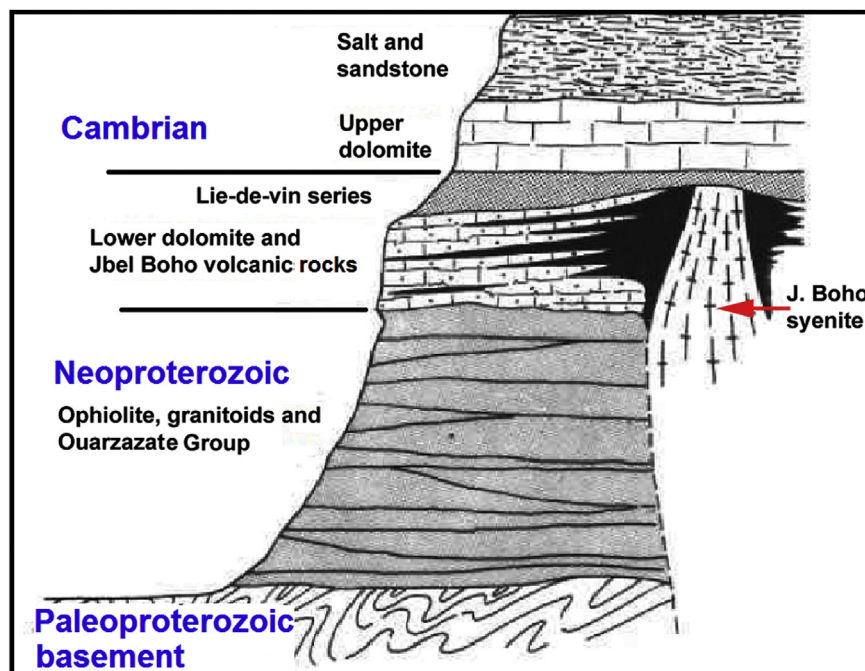


Fig. 4. Stratigraphic column of the Bou Azzer sequence at Jbel Boho. Modified after Ducrot and Lancelot (1977).

the regional geology can be found e.g. in Blein et al. (2014), D'Lemos et al. (2006), El Hadi et al. (2010), Gasquet et al. (2008, 2005) and Villeneuve et al. (2010).

The Jbel Boho alkaline complex consists of three main igneous units: 1) a sequence of lava flows which become progressively more silica-rich up-sequence, 2) a polyphase syenite intrusion cutting the lavas and 3) a late suite of microsyenitic and rhyolitic dykes cutting the older sequence. Fig. 5A shows the geological map of Jbel Boho after Leblanc (1981a) including all sample locations. Fig. 5B is a cross-section from the NE to SW through the Jbel Boho between the early Cambrian lower dolomites (north of the complex), the early Cambrian upper dolomite and Lie-de-vin series (south of the complex). Fig. 6A shows the field relations between the Jbel Boho volcanic rocks and conglomerate. The inclination of the lava flows and the intercalated volcanic breccias and conglomerates is about 30° towards the south. The syenite pluton shows syenitic apophyses (with widths of up to 5 cm) within the adjacent volcanic rocks at the northern limit of the pluton (Fig. 6B and C). The dyke swarm which cross-cut both lavas and pluton have a preferred orientation ranging from N20E to N20W.

We performed systematic sampling through the stratigraphic succession of the Jbel Boho alkaline complex in order to cover all outcropping magmatic rock types for chemical analyses.

3. Petrography of the Jbel Boho rocks

3.1. The alkaline volcanic rocks

The alkaline volcanic rocks sampled along the NE-SW profile

(Fig. 5A) range in composition from basanit/tephrites, trachyandesites, trachytes and trachydacites to alkali rhyolites. The dominant rocks of the complex are trachytes and trachydacites. The most basic members are mainly located in the lower part of the section. They are well exposed in the North (intercalated with the lower dolomites) and in the east along Ouad Tazigzaout (Fig. 5A). Locally, some basic rocks are also found south and northwest of the syenite.

The basanites contain microphenocrysts of olivine and plagioclase in a microlitic groundmass (Fig. 7A). The tephrites and phonotephrites contain larger phenocrysts predominantly of plagioclase (Fig. 7B), with olivine being less abundant or absent. Carbonates in varying amounts are present as secondary minerals.

Most of the extrusive trachytes and trachydacites are very fine-grained and show a porphyritic texture in which large (up to 2 cm) tabular phenocrysts of alkali feldspar are embedded in a very fine-grained alkali feldspar-rich groundmass with quartz filling the interstitial spaces and opaque minerals (Fig. 7C). Only in some samples plagioclase has been identified as phenocryst and groundmass mineral. Secondary chlorite and fluorite are also present. Some chlorite seems to form pseudomorphs after mafic minerals. Some trachytes and trachyandesites show very fine-grained textures with relatively smaller feldspar phenocrysts, reflecting different ascent and crystallization conditions of the magma.

Rhyolites occurring adjacent to the northern margin of the quartz syenite pluton can easily be distinguished in the field from other rock types by their reddish colour. The rhyolite has a texture similar to the trachyte characterized by alkali feldspar phenocrysts, but contains more fine-grained quartz crystals in a groundmass

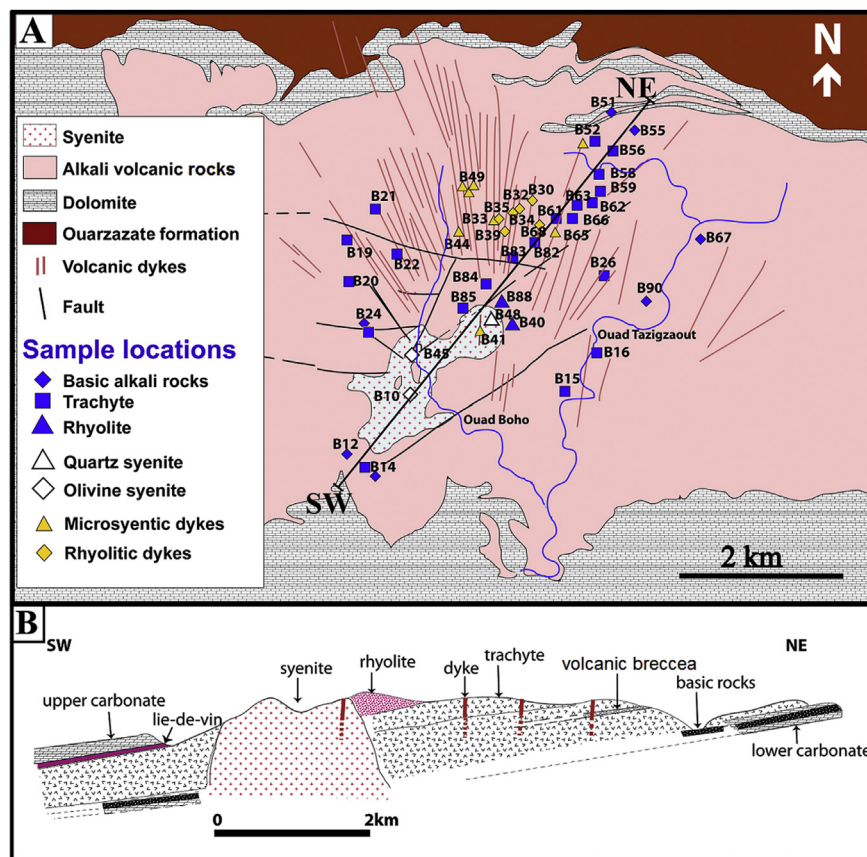


Fig. 5. A Geological map of J. Boho showing the sample locations. B Geological NE-SW cross-section through the Jbel Boho complex showing an inclination of about 30° towards south of the lava flows (trachyte, trachyandesite and trachydacite) and the volcanic breccias presenting relative geochronology from the oldest to youngest rocks toward SW. Map modified after Leblanc (1981a).

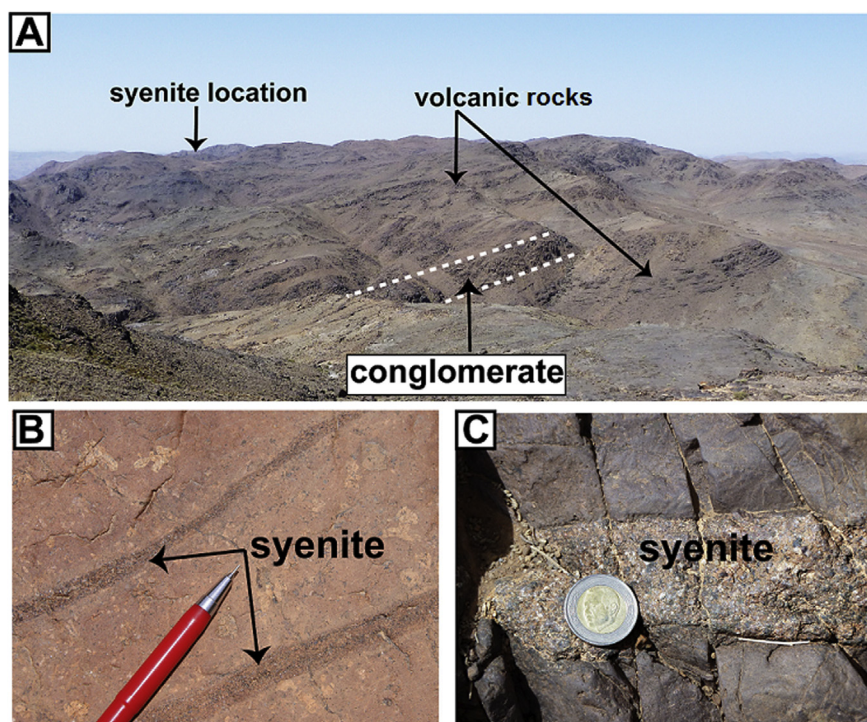


Fig. 6. A Conglomerate deposit with material from surrounding rocks interbedded with the Jbel Boho volcanic rocks, with an inclination about 30° towards south, (view to the SE). B and C, Small syenitic apophyses within the adjoining volcanic rocks at the northern border of the pluton.

dominated by alkali feldspar laths. Aegirine forms poikilitic crystals that include the groundmass feldspar and apatite. A late stage Na-amphibole seems to have grown at the expense of aegirine and contains inclusions of fluorite (Fig. 7D).

3.2. Syenitic intrusion

The syenite pluton of the Jbel Boho complex consists of two rock types: a coarse-grained reddish brown altered porphyritic quartz syenite and a coarse-to medium-grained pinkish altered olivine syenite, which forms the main volume of the pluton.

The quartz syenite (B48, Fig. 7E) contains tabular phenocrysts of alkali feldspar (>70 vol%, grain size of cm-scale), amphiboles and rare Na-pyroxene (aegirine). The main amphibole is a dark green to blue-green Na-amphibole (arfvedsonite), which contains in its core sometimes the brown hornblende and to a lesser extent a pale brownish amphibole (ferrorichterite). The quartz grains (0.5–2 mm in size) are generally interstitial between amphibole and alkali feldspar. Rare Ca-amphibole (hornblende) are also present. The most common accessory mineral is apatite. As a result of the common alteration of aegirine and amphibole, iron oxides have been deposited in microcracks and veins in alkali feldspar.

The olivine syenite crops out in the southern part of the pluton and is easy to identify thanks to its pink colour and coarse-grained texture. Fresh olivine occurs only in some locations, where a grey fresh syenite crops out within the altered pink syenite. The olivine syenite consists of large alkali feldspar grains (up to 5 mm in length) that rarely contain inclusions of plagioclase showing albite twinning. In addition, pale green clinopyroxene (diopside, on average 2–3 mm), late stage brown hornblende and anhedral fayalitic olivine (Fa₅₆₋₆₅; 1–2 mm) are also present (Fig. 7F). Olivine and clinopyroxene are usually rimmed by brown amphibole (rarely green amphibole) and biotite. The main accessory mineral is apatite. The opaque phases are Fe–Ti oxides. Dark small xenoliths

(up to 10 cm) are also found in the olivine syenite. They consist of a similar mineral assemblage as the syenite, but contain minor plagioclase and no hornblende.

3.3. Late intrusives: microsyenitic and rhyolitic dykes

Younger igneous rocks of Jbel Boho are represented by swarms of several vertical to sub-vertical dykes transecting the volcanic rocks and the syenite pluton. The dykes are parallel to sub-parallel and occur mainly on the northern flank of Jbel Boho (Fig. 5A). The dyke thicknesses range from 1 to 5 m. The textures are porphyritic with feldspar phenocrysts. Their compositions generally range from trachyte to trachydacite (often named microsyenitic dykes in the literature) and subalkaline rhyolite. The different types of dykes are very difficult to distinguish in the field, as they all are pink and fine-grained with feldspar phenocrysts.

The microsyenitic dykes trend in N20E to N20W directions and are composed mainly of alkali feldspar phenocrysts (up to 2 cm in size) and interstitial quartz in their feldspar-rich and opaque phase bearing groundmass. The parallel orientation of the groundmass feldspar laths reflects a flow texture. Secondary carbonate and chlorite are also quite common in the groundmass. One sample was found to be quartz free and containing mainly plagioclase as phenocryst (Fig. 7G). Some dykes show feldspar phenocrysts as large as 2 cm in the centre and only up to 0.3 cm at the margin of the dyke.

The subalkaline rhyolitic dykes (represented by samples B30, B32, B34, B35, B39 and B68), which are located near the northern border of the quartz syenite (Fig. 5A) are described here for the first time. These silica-rich dykes seem to trend only in a N–S direction. Alkali feldspar phenocrysts occur in a quartz-rich feldspathic groundmass. Lath shaped chlorite rimmed by opaque phases may represent pseudomorphs after biotite/amphibole phenocrysts. Opaque phases occur dispersed in the groundmass but also

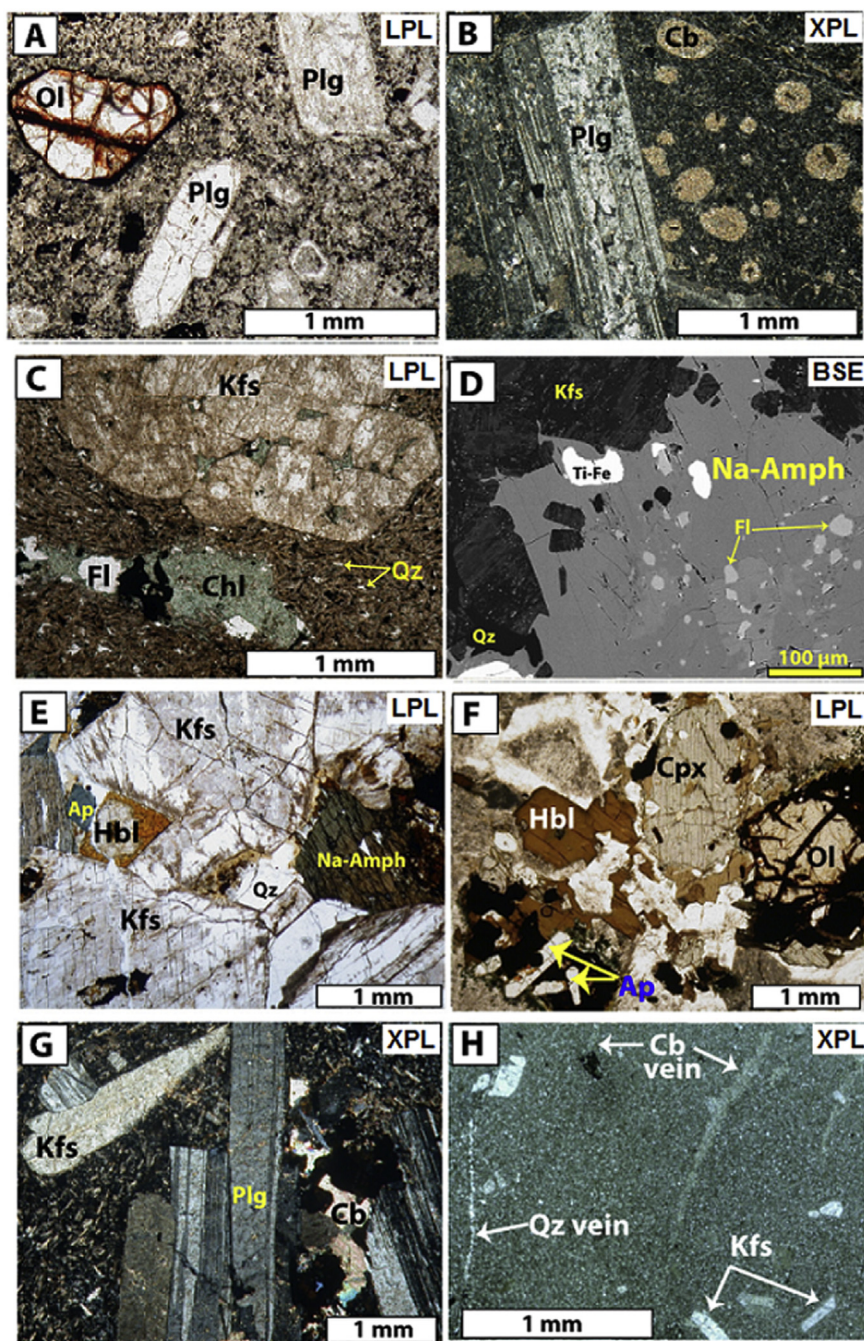


Fig. 7. Photomicrographs of the main Jbel Boho magmatic rocks. A basanite B51-8, B phonotephrite B90, C trachyte B84, D rhyolite B88-2, E quartz syenite B48-3, F olivine syenite B10 G microsyenitic dyke B52 and H rhyolitic dyke B35. Mineral abbreviations from [Whitney and Evans \(2010\)](#). LPL: linear polarized light; XPL: cross polarized light; BSE: backscattered image.

together with calcite as pseudomorphs after mafic minerals. Tiny quartz and carbonate veins are present in many of the late intrusives (e.g. [Fig. 7H](#)).

[Leblanc \(1971\)](#) reported the occurrence of a late E-W lamprophyric dyke south of the syenite pluton cutting both the volcanic and the sediment cover. According to [Leblanc \(1971\)](#) this dyke contains traces of Nb concentrated in biotites. Such dykes have not been sampled during the present study.

4. Analytical methods

A total of 53 samples were analysed for major and trace element

concentrations, presented in [Tables 1–5](#). The whole rock analyses were performed at the ACME Analytical Laboratories Ltd., Vancouver (Canada). Major element were analysed using X-ray fluorescence (XRF) on fused beads, which were prepared with LiBO_2 flux. Determination of Loss on ignition was done on sample splits at 1000°C . The analyses of the trace element concentrations were performed using inductively coupled plasma-mass spectrometer (ICP-MS) with 0.2 g of each sample fused with $\text{LiBO}_2/\text{Li}_4\text{B}_4\text{O}_7$ and 5% HNO_3 . The detection limits for major elements range between 0.001 and 0.1 wt% and for trace elements between 0.01 and 1 ppm. Minerals were analysed using the JEOL JXA 8900R electron microprobe of the Institute of Geosciences, University of Kiel, Germany.

Table 1Major (wt%) and trace element (ppm) contents of basic alkali volcanic rocks of the Jbel Boho complex (*data from W. Schink, pers.com).

Basic alkali volcanics									
Samples	B24-1	B12-2	B51-7*	B51-8	B55-1*	B90	B67	B14-3	B14-1
SiO ₂	46.00	46.50	47.33	47.60	48.68	50.20	50.80	52.70	53.90
TiO ₂	1.32	1.83	2.06	2.03	2.78	1.73	1.92	1.24	1.29
Al ₂ O ₃	16.91	16.20	15.72	15.80	14.63	17.00	16.41	15.80	14.66
Fe ₂ O ₃	15.11	10.94	13.54	11.09	14.01	9.00	9.15	7.18	11.16
MnO	0.32	0.21	0.05	0.06	0.09	0.21	0.11	0.31	0.20
MgO	1.65	3.68	2.89	3.23	2.72	1.62	2.00	1.69	1.82
CaO	4.25	4.16	5.10	6.62	4.43	5.33	5.32	4.28	2.76
Na ₂ O	5.24	4.63	3.45	3.77	5.11	5.41	5.10	3.44	2.55
K ₂ O	2.02	3.66	2.99	2.88	2.97	4.26	3.02	5.49	4.87
P ₂ O ₅	0.41	0.29	1.01	1.02	0.65	0.61	0.60	0.36	0.47
LOI	5.82	7.08	5.65	6.65	2.91	5.30	5.75	6.88	4.88
Total	99.05	99.18	99.79	100.75	98.98	100.67	100.18	99.37	98.56
Ba	108	314	322	87.0	367	296	226	257	325
Rb	34.6	89.2	71.9	66.3	38.7	108	121	138	131
Sr	47.9	232	80.1	95.6	226	121	116	38.5	43.2
Zr	592	307	365	357	248	423	654	669	397
Nb	81.9	48.0	56.3	57.5	46.1	51.8	98.6	93.8	57.5
Ta	5.30	3.20	3.40	3.60	3.00	3.00	5.90	5.90	3.80
Hf	14.0	7.20	7.70	8.80	5.10	8.80	14.4	15.5	9.00
Pb	1.10	0.70	3.40	4.70	3.00	1.10	2.50	0.70	1.50
Th	11.0	5.20	4.00	3.90	4.10	5.80	12.7	12.9	10.4
Cs	0.20	1.40	1.70	2.70	0.20	3.10	1.10	1.90	1.20
U	2.40	3.80	1.20	1.20	2.20	2.00	5.40	3.60	3.50
Co	1.00	8.4	21.7	24.2	17.3	10.4	5.30	1.70	3.70
Zn	11.0	9.0	24.0	25.0	32.0	17.0	10.0	5.0	8.0
La	61.1	42.3	50.2	41.7	25.0	43.4	76.3	79.4	53.5
Ce	123	85.0	106	98.6	61.7	86	157	166	109
Pr	13.7	10.2	13.3	12.4	9.5	10.9	18.3	18.9	12.5
Nd	52.9	36.0	56.4	54.7	46.5	45.4	70.5	74.7	48.6
Sm	10.3	7.7	10.7	11.1	10.1	8.84	13.7	13.9	9.10
Eu	1.90	1.69	3.27	3.52	3.34	2.31	2.10	2.32	2.56
Gd	9.38	6.93	9.64	10.3	8.79	7.93	12.1	12.7	8.66
Tb	1.58	0.97	1.47	1.56	1.24	1.25	2.03	1.97	1.31
Dy	9.72	5.29	7.84	8.68	6.16	7.10	11.3	11.7	7.02
Y	48.7	28.2	39.8	42.8	27.7	33.4	56.7	57.2	39.8
Ho	1.97	1.07	1.66	1.63	1.15	1.27	2.08	2.26	1.47
Er	5.56	2.84	4.42	4.29	2.99	3.66	5.67	6.02	3.84
Tm	0.81	0.44	0.61	0.62	0.45	0.51	0.85	0.88	0.59
Yb	4.99	2.70	4.09	3.81	2.69	3.54	5.51	5.65	3.93
Lu	0.77	0.41	0.60	0.57	0.40	0.54	0.81	0.87	0.57
As	1.70	1.50	5.50	11.50	4.30	3.40	3.30	<0.5	1.00
Ga	40.8	23.1	20.8	19.8	15.3	20.0	30.7	27.1	23.2
Mo	1.00	0.20	1.70	3.70	<0.10	0.20	3.10	5.30	2.60
Cu	0.60	0.60	0.50	0.60	1.60	4.30	1.10	0.70	3.10

The microprobe measurement conditions were 15 kV accelerating voltage and 15 nA beam current.

5. Whole-rock compositions

5.1. Major elements

The Jbel Boho volcanic rocks can be classified on the basis of their total alkali and silica contents (Fig. 8) into basanite, tephrite, phonotephrite, basaltic trachyandesite (summarized as basic alkaline rocks), trachyandesite, trachyte, trachydacite and alkali rhyolite. The subdivision between the alkaline and the subalkaline fields (dashed line in the figure) is after Miyashiro (1978). From the basic to the most acidic volcanic rocks the total alkalis gradually increase and then decrease with increasing SiO₂ contents. The plutonic rocks (olivine bearing syenite and quartz bearing syenite) are also shown in the diagram for comparison. We note that the syenites have higher alkali contents than the volcanic rocks which they intrude. Both syenite types show relatively constant alkali contents over a range in SiO₂ from 53.0 to 62.6 wt%. In contrast, the dykes show a clear decrease in alkalis with increasing SiO₂ and have mainly trachytic to subalkaline rhyolitic compositions.

Major element contents are plotted versus SiO₂ contents in Harker diagrams (Fig. 9). For the volcanic rock series, MgO, FeO, TiO₂, P₂O₅ and CaO contents decrease with increasing silica. The syenites and dykes generally follow these trends, although MgO in the dykes is not correlated with SiO₂ and some dykes have higher CaO at a given SiO₂ than the other rock types. The K₂O contents correlate with silica for all samples except the rhyolitic dykes, which show a negative correlation. The volcanic rocks show no pronounced change in Al₂O₃ with increasing silica up to ca. 62 wt% SiO₂, after which Al₂O₃ then strongly decreases. This decrease is mimicked by the dykes.

The olivine syenites do not lie on this trend and have significantly higher Al₂O₃ contents than all other studied rocks. Na₂O displays no systematic variations with SiO₂ in the volcanic rocks, but shows a strong negative relationship in the syenites and dykes. The quartz syenite and the microsyenitic dykes have, with the exception of high CaO contents in some of the latter, very similar major element compositions.

The olivine syenite and the quartz syenite have similar FeO contents and except the higher SiO₂ and K₂O content in the quartz syenite, the latter have generally lower contents in the other major elements than the olivine syenite (Fig. 9).

Table 2

Major (wt%) and trace elements (ppm) contents of trachyandesites, trachydacites and trachytes.

Trachyandesite to trachyte											
Samples	B14-2	B20	B19	B26-1	B52	B63	B16	B62	B15	B82	B22-1
SiO ₂	54.60	58.40	58.90	59.30	59.62	61.90	61.90	62.05	62.80	62.70	63.80
TiO ₂	1.41	0.89	0.89	1.01	0.94	0.46	0.53	0.40	0.35	0.57	0.40
Al ₂ O ₃	16.68	16.03	16.59	15.63	16.04	15.42	16.59	15.06	14.89	15.03	15.89
Fe ₂ O ₃	7.10	6.60	6.85	7.67	6.88	8.27	5.16	6.26	6.15	5.30	6.68
MnO	0.16	0.09	0.13	0.14	0.07	0.06	0.06	0.24	0.11	0.06	0.11
MgO	1.51	1.04	0.94	0.85	1.39	0.47	0.74	0.55	0.58	0.90	0.03
CaO	3.29	2.79	2.09	1.66	2.24	1.15	1.29	1.09	2.45	2.44	0.31
Na ₂ O	4.91	5.96	6.15	5.31	6.03	5.97	5.66	4.63	6.09	2.24	6.24
K ₂ O	4.45	4.38	4.65	5.77	3.83	5.08	5.42	6.64	2.77	8.10	4.69
P ₂ O ₅	0.55	0.23	0.22	0.27	0.27	0.05	0.14	0.05	0.03	0.09	0.04
LOI	4.67	2.98	1.94	1.69	2.47	1.89	1.69	0.95	3.09	3.15	0.99
Total	99.33	99.39	99.35	99.3	99.78	100.72	99.18	97.92	99.31	100.58	99.18
Ba	217	547	692	519	375	144	619	191	110	704	226
Rb	91.0	92.0	90.3	80.6	43.5	75.4	107	127	58	182	76.8
Sr	99.3	108	136	44.7	105	35.5	153	52.6	33.7	34.9	28.5
Zr	426	544	549	294	322	456	572	528	590	459	833
Nb	61.9	98.6	89.9	46.7	63.6	78.8	80.3	96.2	97.6	90.3	154
Ta	4.00	7.30	6.30	3.30	3.90	5.40	5.00	6.50	6.70	6.00	10.3
Hf	10.4	13.3	14.0	7.40	8.50	11.1	14.6	12.5	15.4	11.1	19.0
Pb	1.40	2.50	3.60	11.8	3.80	2.90	2.50	6.80	2.70	2.00	6.00
Th	10.5	15.3	13.1	5.20	6.00	12.1	14.4	14.6	11.0	12.8	21.1
Cs	0.70	0.50	0.50	1.30	0.30	0.40	0.60	0.40	0.50	0.80	0.40
U	3.30	4.70	3.90	1.30	2.50	5.60	4.00	3.10	1.70	2.20	4.60
Co	3.20	4.50	6.20	1.90	8.20	0.40	2.70	0.60	<0.20	0.60	1.10
Zn	11.0	20.0	81.0	74.0	19.0	29.0	21.0	33.0	23.0	8.0	8.0
La	27.6	68.6	76.5	41.9	26.6	67.8	73.7	70.3	87.2	61.7	139
Ce	59.8	137	150	89.6	55.5	132	145	140	177	115	262
Pr	7.17	15.5	17.1	10.5	7.56	16.0	16.2	17.6	20.0	14.0	30.3
Nd	27.7	59.6	63	41	34.3	63.6	60	67.5	79	53.2	117.6
Sm	6.14	11.2	11.7	7.70	7.24	11.0	11.2	12.6	14.1	10.7	21.5
Eu	1.34	2.12	2.47	3.31	1.91	1.45	2.46	1.19	0.95	1.71	2.26
Gd	6.72	10.6	10.9	7.29	6.29	9.81	9.69	11.2	13.0	10.1	17.8
Tb	1.19	1.65	1.61	1.1	1.06	1.67	1.52	1.83	2.08	1.7	2.63
Dy	7.46	10.1	9.38	5.59	6.38	9.67	9.6	9.96	12.7	9.55	16.5
Y	42.1	53.2	52.1	30.2	28.8	50.3	47.7	53.4	73.4	52.5	82.9
Ho	1.55	2.06	1.95	1.17	1.21	1.97	1.93	2.02	2.88	1.95	3.21
Er	4.00	5.87	5.68	3.15	3.4	5.5	5.54	5.49	8.31	5.86	8.7
Tm	0.63	0.9	0.83	0.44	0.52	0.82	0.8	0.77	1.24	0.85	1.23
Yb	3.94	5.77	5.45	2.76	3.34	5.04	5.12	5.72	6.98	5.83	8.04
Lu	0.58	0.82	0.81	0.43	0.52	0.8	0.75	0.83	1.04	0.79	1.17
As	4.50	1.00	3.40	1.90	<0.50	1.60	0.80	3.60	4.80	1.10	4.20
Ga	22.7	24.6	25.4	24.5	24.6	30.8	24.1	30.2	34.2	25.8	29.8
Mo	1.20	2.30	1.80	2.70	0.80	1.90	1.60	1.20	1.50	0.40	0.50
Cu	3.30	3.40	29.60	1.80	0.90	4.30	10.50	4.50	4.80	15.60	1.80

5.2. Trace and rare earth elements geochemistry

The genetic relationships of the Jbel Boho rocks can also be examined using trace elements. To minimize the effects of post-crystallization element mobility on these studies, we have concentrated on the high-field-strength elements (HFSE) as they are alteration-resistant and not readily removed in solution as hydrated cations. Consistent with the TAS plot, the magmatic rocks show an alkaline affinity on the Zr/Ti vs Nb/Y diagram of [Pearce \(1996\)](#) (Fig. 10).

The HFSE (Nb, Zr, Ta, Hf) show very similar distribution in the Jbel Boho igneous rocks. They display little increase with increasing SiO₂ especially at SiO₂ above 60 wt%, after which the HFSE contents increase steadily. An exception to this statement is some of the microsyenite dykes, which show significantly higher HFSE concentrations (Fig. 11). From the olivine syenite to the quartz syenite there is only a slight decrease of the HFSE content.

In Fig. 12, the Nb/Ta and Zr/Hf ratios are plotted as function of SiO₂ and TiO₂ in order to understand the inter-element fractionation during differentiation. Nb/Ta and Zr/Hf ratios generally decrease with increasing SiO₂ in all rock types with the exception of

the rhyolitic dykes, which show relatively constant Zr/Hf of 40. Nb/Ta ratios show a clearer negative correlation with SiO₂ content, for all rock groups, including rhyolitic dykes. Relative to TiO₂, the two HFSE ratios show weak positive trends.

On the tectonic discrimination diagram Ti–Zr after [Pearce \(1982\)](#) and the 2Nb–Zr/4–Y diagram after [Meschede \(1986\)](#) the Jbel Boho rocks lie in the field for rocks from an intraplate tectonic setting (Fig. 13).

The similarity in trace element signatures of all Jbel Boho rocks is evident from the normalized REE and trace element plots shown in Fig. 14. The chondrite ([Boynton, 1984](#)) normalized REE diagrams (left hand side of Fig. 14) show strong enrichment of the LREE relative to the HREE and similar types of REE patterns with a ratio of LREE/HREE > 1 is evident in all samples. The diagrams are presented in stratigraphical order of the Jbel Boho magmatic rocks to facilitate the understanding of the geochemical evolution of the entire complex.

The basic volcanic rocks show no or only slightly negative Eu anomalies with Eu/Eu* from 0.5 to 1. The trachyandesites, trachytes and rhyolites display strong negative Eu anomalies, with Eu/Eu* from 0.2 to 0.7, with the exception of sample B26-1 that has Eu/Eu*

Table 3

Major (wt%) and trace elements (ppm) contents of selected trachytes and rhyolites.

Trachyte to rhyolite												
Samples	B31	B56-2	B85-2	B84	B58	B56-1	B66	B83	B59	B24-2	B88-2	B40-3
SiO ₂	64.10	64.53	65.9	64.8	65.11	66.18	66.1	66.6	67	68.7	70.8	71.2
TiO ₂	0.42	0.44	0.36	0.54	0.42	0.45	0.42	0.45	0.37	0.41	0.3	0.28
Al ₂ O ₃	15.58	14.45	14.63	15.46	13.9	14.76	14	13.03	13.2	12.53	12.19	12.11
Fe ₂ O ₃	7.34	4.89	7.53	6.38	5.88	6.23	5.46	5.83	6.06	5.23	4.98	4.78
MnO	0.10	0.04	0.08	0.03	0.05	0.04	0.06	0.06	0.06	0.03	0.11	0.10
MgO	0.17	0.6	0.1	0.71	0.69	0.26	0.39	0.83	0.66	0.44	0.06	0.05
CaO	0.72	1.71	0.19	0.74	1.84	0.33	1.05	2.33	1.93	0.55	0.63	0.63
Na ₂ O	6.32	3.64	4.75	4.6	4.55	6.01	1.99	2.84	3.65	1.48	4.67	3.68
K ₂ O	4.75	6.63	5.72	5.31	4.56	3.91	8.85	5.15	4.57	7.00	5.29	5.90
P ₂ O ₅	0.05	0.04	0.03	0.08	0.03	0.04	0.03	0.03	0.03	0.04	0.02	<0.01
LOI	0.85	2.21	0.96	1.82	2.3	0.91	1.96	3.61	2.82	2.15	0.61	0.67
Total	100.4	99.18	100.25	100.47	99.33	99.12	100.31	100.76	100.35	98.56	99.66	99.4
Ba	166	579	380	272	333	247	598	227	263	273	77.0	76.0
Rb	77.1	125	103	103	86.3	66.9	148	110	100	112	217	189
Sr	44.7	62.9	18.5	25.4	52.2	40.5	27.7	26.5	57.7	23.7	16.6	32.2
Zr	406	550	649	526	746	535	698	816	697	1586	1046	860
Nb	89.5	95.5	105	90.3	123	93.8	118	132	113	230	141	123
Ta	6.10	6.70	7.60	6.30	8.00	7.00	8.00	9.70	7.60	17.4	12.0	13.4
Hf	10.9	13.8	16.9	12.9	17.8	14.9	16.7	20.8	16.6	40.5	26.8	29.2
Pb	5.80	6.00	4.50	1.30	12.0	5.10	16.7	3.20	5.50	2.20	11.7	6.30
Th	9.00	13.9	16.3	12.1	15.7	15.9	14.0	21.8	17.6	49	35.1	28.1
Cs	0.50	0.80	0.60	0.70	0.40	0.50	0.90	0.70	1.10	0.60	0.80	1.60
U	0.70	3.30	6.60	3.80	1.60	5.30	3.40	4.50	10.5	14.7	7.60	4.80
Co	0.20	2.20	11.20	3.40	7.00	1.00	1.00	0.90	1.70	2.60	0.50	0.30
Zn	24.0	7.0	4.0	8.0	13.0	5.0	11.0	11.0	13.0	6.0	57.0	112
La	74.1	92.1	118.2	67.1	95.9	127.9	221.1	98.1	103	178.6	138.2	150.8
Ce	156	179	219	135	190	201	448	194	195	328	259	302
Pr	17.6	20.9	25.0	15.2	22.8	26.7	49.8	22.5	24.7	33.9	30.6	33.1
Nd	73.7	75.7	94.9	62.0	82.0	95.9	190	85.6	97.7	111	117	122
Sm	12.63	12.77	16.29	11.56	15.96	16.55	35.28	16.08	18.6	19	20.88	22.86
Eu	1.27	1.34	1.44	1.58	1.3	2.02	3.21	1.72	1.67	2.43	1.18	1.12
Gd	10.8	9.97	13.8	10.2	13.9	13.8	29.7	15.1	16.1	18.5	19.2	21.3
Tb	1.76	1.55	1.89	1.52	2.25	2.1	3.61	2.87	2.54	3.99	3.36	3.33
Dy	10.1	9.01	11.2	8.2	13.5	11.0	16.2	16.3	13.6	28.7	21.4	20.1
Y	48.8	55.5	60.1	46.9	75.7	59.1	76.7	83.1	65.4	158	116	111
Ho	2.02	1.99	2.29	1.76	3.00	2.20	2.76	3.22	2.48	6.19	4.34	4.03
Er	5.45	6.09	6.76	5.33	8.06	6.23	7.96	8.73	6.88	17.35	12.81	11.36
Tm	0.80	0.90	1.06	0.85	1.14	0.91	1.24	1.29	1.00	2.44	1.87	1.78
Yb	5.29	5.66	6.91	5.92	7.25	6.02	8.24	7.97	6.65	14.68	10.88	10.81
Lu	0.79	0.83	1.00	0.82	1.03	0.81	1.08	1.17	0.95	2.05	1.48	1.53
As	5.00	0.80	1.30	1.80	1.10	1.20	1.60	2.80	0.80	4.40	4.90	0.90
Ga	32.2	29.4	24.7	30.6	32.8	31.6	22.7	36.6	29.8	19.1	33	32.1
Mo	0.80	1.90	0.60	1.40	1.00	0.70	0.60	5.20	1.70	5.20	1.20	8.90
Cu	0.60	0.80	286	149	13.5	0.60	90.2	3.80	1.10	2.80	2.40	4.90

about 1.3. All syenite samples but one (B45 with Eu/Eu* about 1.3) show only very weak negative Eu anomalies (Eu/Eu* between 0.75 and 0.95). The microsyenitic and rhyolitic dykes display pronounced negative Eu anomalies (Eu/Eu* between 0.2 and 0.5). One rhyolite dyke (B35, see Fig. 5) shows very high LREE contents, with e.g., Ce up to 720 ppm. This LREE enrichment is associated with the presence of the secondary LREE–Ca–F–carbonate mineral synchysite that is fine-grained and occurs in the groundmass and in tiny carbonate veins or associated with chlorite and opaques.

The primitive mantle (McDonough and Sun, 1995) normalized trace element diagrams (right hand side of Fig. 14) show similar sub-parallel patterns with negative Ti, P, Sr, Pb and Ba anomalies for all rocks except for the syenites, in which the negative anomalies of these elements are less pronounced. In contrast to all other Jbel Boho igneous rocks, the quartz syenite shows only small negative or even distinctly positive Pb anomalies.

6. Mineral chemistry

Unlike the other differentiated alkaline volcanic rocks of Jbel Boho, which show strong negative Eu anomalies, the quartz syenite

shows no Eu anomaly and the olivine syenite shows a slight negative to positive Eu anomaly (Fig. 14). Among the late intrusives one rhyolitic dyke (B35) displays much higher LREE contents than all other analysed rocks of Jbel Boho (Fig. 14).

In order to better understand how the two types of syenites in particular fit into the magmatic evolution of the Jbel Boho complex and also to identify the minerals that are responsible for the high enrichments of LREE in dyke B35, microprobe analyses of the main minerals in the syenites and of the accessory REE mineral synchysite in the dyke B35 were performed. The mineral compositions of olivine, amphibole, clinopyroxene and synchysite are given in Tables 6–9.

6.1. Olivine

Olivine of the olivine syenite in Jbel Boho is anhedral, between 0.1 and 2 mm in size and is surrounded by broad rims of biotite and hornblende. Microprobe analyses show a fayalitic olivine without regular zoning, although at the border higher Fe contents were sometimes detected, resulting likely from alteration and oxidation. The fayalite contents in individual olivines vary slightly by up to

Table 4

Major (wt%) and trace elements (ppm) contents of quartz syenite, olivine syenite and microsyenitic dykes.

Samples	Qz-syenite				Ol-syenite		Microsyenitic dykes			
	B48-2	B48-3	B48-4	B48-5	B10	B45	B33	B41	B44-1	B44-2
SiO ₂	62.00	61.90	62.60	62.30	53.00	55.60	65.70	64.80	61.70	65.10
TiO ₂	0.68	0.70	0.62	0.61	1.54	0.83	0.60	0.42	0.67	0.61
Al ₂ O ₃	15.49	15.42	16.09	15.98	18.36	20.15	13.94	13.58	14.97	13.08
Fe ₂ O ₃	6.95	6.95	5.77	5.41	7.63	4.44	4.31	2.57	2.34	2.08
MnO	0.24	0.27	0.28	0.09	0.18	0.11	0.06	0.08	0.10	0.11
MgO	0.52	0.51	0.46	0.95	1.64	0.85	1.54	0.35	0.33	0.15
CaO	1.37	1.42	1.12	1.70	4.31	4.13	2.11	4.53	5.09	5.13
Na ₂ O	5.95	5.84	5.56	5.57	6.62	7.36	4.39	5.08	5.08	4.31
K ₂ O	5.55	5.79	5.83	5.52	4.20	3.63	4.01	4.45	5.31	5.21
P ₂ O ₅	0.16	0.15	0.19	0.15	0.42	0.24	0.10	0.05	0.12	0.05
LOI	1.17	1.26	1.90	2.40	1.13	1.49	2.99	4.12	4.71	4.75
Total	100.08	100.21	100.42	100.68	99.03	98.83	99.75	100.03	100.42	100.58
Ba	772	877	980	939	325	463	219	301	322	284
Rb	91.5	94.2	92.3	80.9	78.6	62.6	75.6	68.7	93.0	83.4
Sr	143	154	161	142	464	689	34.0	39.8	54.7	48.0
Zr	447	469	305	465	730	484	731	669	1307	2063
Nb	78.6	81.7	58.1	76.5	110	75.8	112	111	209	317
Ta	5.70	5.50	3.90	5.30	6.80	4.70	8.30	8.20	14.5	21.5
Hf	11.3	10.5	7.2	11.1	14.8	9.9	19.2	16.6	30.9	48
Pb	33.6	45.8	12.6	5.6	4.8	2.9	1.3	1.8	2.8	2.9
Th	9.90	11.0	6.40	10.7	13.4	9.00	21.8	16.8	30.7	50.4
Cs	1.70	3.00	2.40	1.30	2.20	1.40	0.50	0.30	0.50	0.50
U	2.90	3.00	2.30	2.80	4.10	2.80	6.30	4.10	8.40	13.6
Co	2.10	1.60	1.90	2.30	11.6	5.50	6.80	1.70	1.00	0.60
Zn	143	147	582	43.0	20.0	19.0	11.0	5.00	8.00	10.0
La	61.8	60.1	50.6	58.9	66.6	50.6	129.7	66.8	116.5	141
Ce	128	122	106	118	134	93.8	257	142	234	286
Pr	15.2	14.5	12.5	14.0	14.8	10.3	28.9	16.4	26.4	32.0
Nd	61.1	56.1	50.5	58.1	51.8	35.5	109.7	63.5	94.2	122
Sm	11.3	10.7	9.29	10.3	10.3	6.54	19.8	13.1	17.5	23.1
Eu	2.83	2.84	2.82	2.81	2.46	2.88	2.07	2.18	2.09	2.70
Gd	9.21	9.4	8.22	8.99	9.06	6.16	15.49	11.89	14.47	20.54
Tb	1.59	1.55	1.29	1.53	1.42	1.00	2.32	2.11	2.62	4.03
Dy	8.97	8.89	7.40	8.75	8.37	5.53	13.2	12.6	16.4	27.1
Y	47.1	48.4	35.9	46.0	46.0	30.6	73.5	65.1	90.7	148
Ho	1.78	1.71	1.44	1.68	1.63	1.13	2.45	2.45	3.41	5.57
Er	5.01	4.98	3.86	4.75	4.71	3.16	7.73	7.07	10.18	16.16
Tm	0.75	0.75	0.6	0.73	0.73	0.47	1.08	1.03	1.57	2.43
Yb	5.04	4.90	3.77	4.97	4.67	3.15	6.84	6.86	10.1	16.2
Lu	0.73	0.72	0.58	0.66	0.65	0.47	0.98	0.97	1.49	2.35
As	4.30	4.30	2.80	2.90	2.40	1.30	0.50	0.60	0.80	1.50
Ga	29.7	29.2	29.7	29.2	30.0	27.3	26.3	22.3	31.3	23.2
Mo	2.60	2.70	2.50	3.50	5.70	4.20	1.50	4.20	3.00	2.10
Cu	1.90	2.40	2.20	13.4	10.4	5.20	4.30	3.20	0.90	2.90

~3 mol % from Fa₅₆ to Fa₅₉ (Table 6; 1–5) and reach Fa₆₁ at the rim. In some olivines (e.g., Table 6; 7–10) the fayalite contents are somewhat higher in the range of Fa₆₁ to Fa₆₂ with higher fayalite content at the rim (Fa₆₅). Low contents of Mn (MnO ~ 2 wt%) are present leading to calculated tephroite contents.

6.2. Amphibole

Two types of amphibole can be distinguished optically in the syenites: greenish to pale brownish Na-amphibole in the quartz syenite and brownish Ca-amphibole in the olivine bearing syenite.

The Na-amphiboles in the quartz syenite have two distinct compositions: the pale brownish amphibole (Table 7; #1–#4) with TiO₂ contents of 1–3 wt%, CaO of 4–5 wt% and Mg/(Mg + Fe²⁺_{tot}) is mostly smaller than 0.1 and the greenish amphibole (Table 7, #5–#9) with TiO₂ around 0.4 wt%, CaO between 1 and 3 wt% and Mg/(Mg + Fe²⁺_{tot}) from 0.02 to 0.03. After Hawthorne and Oberti (2007) the pale brownish amphiboles can be classified as ferrocichterite and the greenish amphiboles as arfvedsonite.

The Ca-amphibole (brown hornblende) in the olivine syenite is more abundant in the rock than olivine and both minerals have

similar grain sizes (up to 2 mm). In contrast to the amphiboles of the quartz syenite, these amphiboles have much higher Al₂O₃, MgO and Mg/(Mg + Fe²⁺) contents and less SiO₂ and FeO contents, with TiO₂ contents in the range 2.9–3.1 wt% and intermediate Mg/(Mg + Fe²⁺_{tot}) of around 0.5 (Table 7, #10–#15). The Ca-amphibole in the olivine syenite can be termed titanian ferropargasite.

6.3. Clinopyroxene in olivine-syenite

Clinopyroxene is the predominant mafic phase in the olivine syenites. Analyses of selected pyroxenes (Table 8) revealed compositions of Wo_{48–49} to En_{33–38} and Fs_{12–19}. The Al₂O₃ content is between 1.8 and 3.5 wt% and X_{Mg} (Mg/(Mg + Fe²⁺_{tot})) between 0.6 and 0.7, which is slightly more magnesian than the coexisting hornblende. TiO₂ is present up to 1.7 wt% and small amounts of, Na and Mn were also detected. According to the high Wo composition these clinopyroxenes can be classified as diopside.

6.4. Feldspar

The dominant mineral in the Jbel Boho syenite is perthitic alkali

Table 5

Major (wt%) and trace elements (ppm) contents of microsyenitic (contid. From Table 4) and rhyolitic dykes.

Samples	Microsyenitic dykes					Rhyolitic dykes					
	B52-4	B65-1	B49-1	B-49-2	B49-3	B30	B32	B34	B35	B39	B68
SiO ₂	59.39	66.1	60.4	61.2	65.6	73.7	70.3	75.8	78.3	72.6	71
TiO ₂	1.14	0.34	0.77	0.82	0.55	0.28	0.46	0.3	0.28	0.33	0.36
Al ₂ O ₃	17.51	16.14	13.24	13.97	13.84	11.31	12.98	10.02	9.77	10.27	12.95
Fe ₂ O ₃	4.37	4.78	7.3	5.76	4.85	2.26	3.65	2.48	2.84	2	3.94
MnO	0.06	0.01	0.15	0.12	0.07	0.04	0.04	0.05	0.02	0.05	0.02
MgO	1.14	0.72	0.97	1.22	1.38	1.29	1.2	1.03	1.22	0.33	1.31
CaO	2.93	0.19	4.07	4.67	1.82	1.94	1.2	2.04	0.72	3.48	0.53
Na ₂ O	6.72	3.88	4.95	5.38	4.27	2.4	3.21	1.84	4.19	2.42	2.35
K ₂ O	4.31	6.86	2.76	2.38	4.77	3.32	4.97	3.8	1.21	4.73	5.46
P ₂ O ₅	0.37	0.04	0.1	0.09	0.06	0.01	0.05	<0.01	<0.01	<0.01	0.02
LOI	2.17	1.68	4.71	4.89	3.26	3.47	2.41	2.96	1.7	3.82	2.37
Total	100.11	100.74	99.42	100.50	100.47	100.02	100.47	100.32	100.25	100.03	100.31
Ba	1162	382	105	133	194	172	299	145	56.0	236	235
Rb	48.2	147	77.7	40.4	77.6	108	103	110	25.5	83	125
Sr	135	41.1	32.5	36.6	19.3	98.0	28.9	21.3	22.1	26.4	18.3
Zr	533	996	1492	1432	779	1103	964	1362	1387	1372	1565
Nb	77.3	140	263	262	132	147	153	201	192	207	235
Ta	5.40	8.40	17.6	18.5	8.40	12.0	11.9	15.4	15.0	15.3	17.0
Hf	10.7	24.4	35.7	35.6	18.2	26.8	25.6	34.4	32.9	34.4	36.6
Pb	2.20	3.30	3.60	2.70	4.90	2.00	1.80	1.60	1.90	2.90	1.40
Th	13.9	22.7	39.4	41.1	17.2	33	29	36.9	40.9	43.5	35.3
Cs	0.40	1.80	0.60	0.20	0.40	1.90	0.90	1.30	0.40	0.80	1.00
U	21.8	5.30	12.1	13.1	5.70	12.5	8.30	11.8	10.1	9.00	9.60
Co	6.30	0.80	2.00	1.90	13.5	5.60	4.30	4.90	6.40	2.60	1.80
Zn	26.0	7.00	21.0	21.0	6.00	8.00	10.0	7.00	7.00	4.00	8.00
La	115	58.3	167	84.2	56.3	83.3	111	150	378	81.7	89.7
Ce	219	114	323	191	117	169	214	284	719	162	172
Pr	25.1	14.1	35.7	21.0	13.7	19.5	24.7	31.8	84.5	18.5	20.3
Nd	97.1	59.0	130.7	78.9	54.1	73.8	90.3	113.3	335.6	68.8	79.1
Sm	11.2	13.0	21.9	17.0	10.4	13.8	16.5	20.6	52.8	14.8	15.6
Eu	2.24	1.54	1.77	2.12	1.64	2.29	1.46	1.32	7.45	1.97	1.66
Gd	7.53	15.56	17.61	17.56	9.73	13.4	13.93	16.82	35.73	15.21	16.81
Tb	1.14	3.30	3.16	3.20	1.83	2.99	2.41	3.01	4.07	3.08	3.88
Dy	6.97	19.3	19.7	20.3	12.2	19.4	14.7	19.2	21.4	20.3	26.6
Y	35.5	93.2	106	110	67.7	99.1	90.3	123	125	121	133
Ho	1.44	3.65	3.97	4.08	2.69	3.93	3.12	4.22	4.31	4.39	5.32
Er	4.07	9.69	12.0	11.9	8	10.9	9.43	12.3	13.0	13.4	15.3
Tm	0.68	1.37	1.81	1.84	1.17	1.58	1.48	1.98	2.02	1.97	2.18
Yb	4.49	8.44	11.74	12.51	7.34	10.32	8.78	12.35	12.52	12.24	13.24
Lu	0.65	1.26	1.65	1.68	1.09	1.35	1.27	1.7	1.73	1.64	1.85
As	1.60	0.80	3.80	1.50	5.60	7.10	1.50	<0.50	3.10	3.40	2.00
Ga	22.2	33.5	35.3	29.3	25.0	24.9	26.7	33.4	12.1	19.6	41.8
Mo	0.70	0.40	11.0	8.40	4.80	3.00	0.80	0.40	<0.10	0.30	<0.10
Cu	1.10	0.90	17.9	63.5	4.00	0.60	9.70	0.50	1.30	1.10	15.5

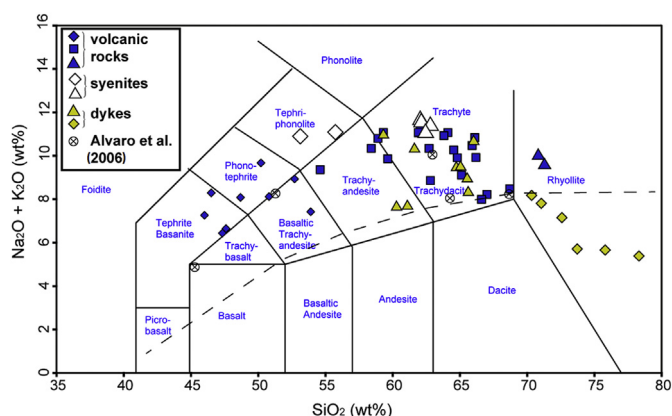


Fig. 8. TAS diagram showing the compositional fields of the alkaline rocks of the Jbel Boho complex. Some rhyolitic dykes have high SiO₂ and low alkali contents. The data of Alvaro et al. (2006) are added for comparison. The alkaline subalkaline dashed line is from Miyashiro (1978).

feldspar with patchy recrystallized exsolutions precluding the determination of the bulk chemistry.

6.5. Synchysite

This REE mineral synchysite is found in one dyke B35, which is intruded by tiny quartz and carbonate veins (Fig. 7H). The different occurrences of synchysite within the dyke are summarized in Fig. 15. The synchysites are anhedral to subhedral with grain sizes in the range from 10 to 300 μm . They are mainly associated with quartz and chlorite within the groundmass (Fig. 15A–C) and some occur within Fe-oxide bodies together with chlorite (Fig. 15D). Representative analyses are reported in Table 9. A fixed amount of 26.5 wt% CO₂ is added to each individual microprobe analysis corresponding to the average CO₂ content of synchysite after Guastoni et al. (2009). The highest average rare earth element content in synchysite, expressed as oxide, is 20.35 wt% Ce₂O₃. La and Nd are also enriched with averages of 12.53 wt% La₂O₃ and 10.6 wt% Nd₂O₃. The resulting structural formula with 0.99 atoms REE, 1.09 Ca, 1.99 C and 0.86 F ($\Sigma\text{REE}_{0.99}\text{Ca}_{1.09}(\text{CO}_3)_{1.99}\text{F}_{0.86}$) corresponds very closely to the composition of the REE–Ca–F carbonate

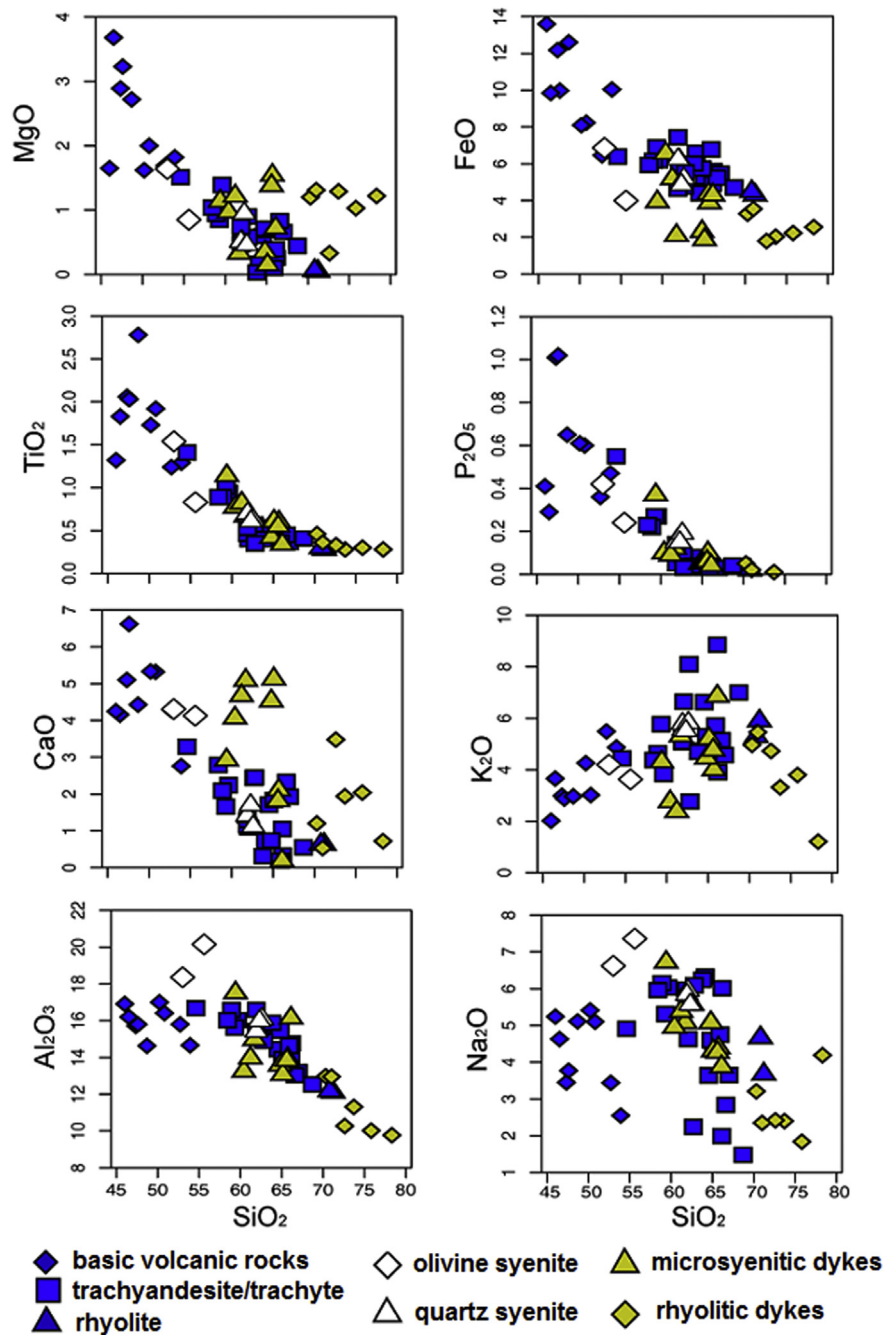


Fig. 9. Harker variation diagrams for the rocks of the J. Boho alkaline complex. The magmatic evolution of the complex is reflected by the increase of SiO_2 .

mineral synchysite that belongs to the bastnäsite group. According to Guastoni et. (2009) the missing pfu 0.14 of F are related to OH content.

7. Discussion

7.1. Sources and magma generations

The first studies of the Jbel Boho complex were reported by Choubert (1952), Leblanc (1971, 1981a). These studies were mainly restricted to petrographical observations and described the main volcanic rocks as andesites. Our geochemical work revealed no andesites at Jbel Boho and instead highlights the alkaline nature of these rocks shown on both the TAS diagram (Fig. 8) and the

alteration-resistant HFSE ratio plot (Fig. 10), in agreement with the data presented as average values by Álvaro et al. (2006).

The similarities in incompatible trace element ratios in all Jbel Boho magmas suggest that the complex as a whole is derived from one source type. The most primitive volcanic rocks (low SiO_2) of Jbel Boho have high enrichment of the LREE relative to the depleted HREE and very high Nb/Ta and Zr/Hf ratios. This may indicate a garnet bearing mantle source from which LREE-enriched alkali basalt and alkali volcanic rocks are derived by low degrees of partial melting as originally demonstrated by the model calculations of Kay and Gast (1973). The Zr/Hf and Nb/Ta ratios of the rocks of lower SiO_2 contents (Fig. 12) are higher than the Zr/Hf chondritic values (34.3) and below the Nb/Ta chondritic values (19.9). This data suggest the mantle source of these alkaline rocks to be similar

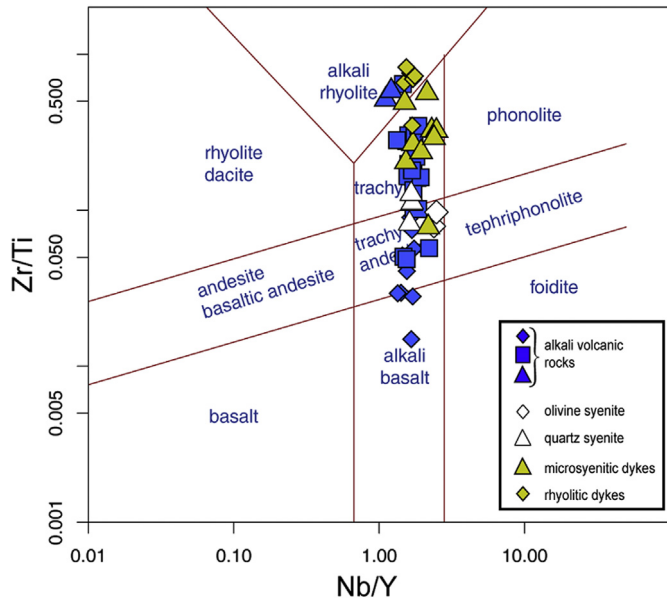


Fig. 10. The Zr/Ti versus Nb/Y classification diagram after Pearce (1996) show alkaline magmatic affinity for the Jbel Boho magmatic rocks.

to that of hot spot or plume-related ocean island basalts (OIB) and continental basalts (Münker et al., 2003; Pfänder et al., 2007). These lower silica rocks must be differentiated otherwise with olivine that would be closer to 70–80 wt% Fo. However the olivines in

syenite are Fa-rich and are too felsic to have been in equilibrium with mantle mineralogy. This syenite was likely fractionated on the way up in the crust (see paragraph below: *syenite petrogenesis*).

The oldest magmatic rocks in the Jbel Boho complex are the lavas. The data in the TAS diagram and their correlation with the stratigraphic position of the analysed samples suggest an evolution of an alkaline magmatic system from basanite and tephrite to trachyte and rhyolite during the eruption of the volcanic rocks.

The volcanic rocks were then intruded by a syenitic pluton consisting of an olivine syenite and a quartz syenite magma body. The syenites do not continue the fractionation trend seen in the proceeding volcanic sequence. In addition to the lower silica and higher Fe and Mg contents of the olivine syenite relative to the rhyolites, both syenites also have very different rare earth and trace elements patterns when compared to the volcanic rocks. This can be seen, for example, in much more subdued Eu and Ba anomalies and some positive Pb anomalies in the syenites (Fig. 14). This is strong evidence that the magma from which the syenites were formed represents a second generation of melt. Although the two types of Jbel Boho syenite in the field appear to belong to the same pluton, they are mineralogically and chemically distinct.

Both volcanic rocks and syenite are cut by microsyenitic and rhyolitic dykes. The microsyenitic dykes display, in many cases, generally the same major element contents as the quartz syenite and are very similar to them in terms of HFSE ratios. Nevertheless, the presence of plagioclase in some of the dykes contrasts with its general absence in the syenitic pluton and the much higher HFSE-contents of some microsyenitic dykes at similar SiO₂ contents (Fig. 11) suggest that they are not directly related.

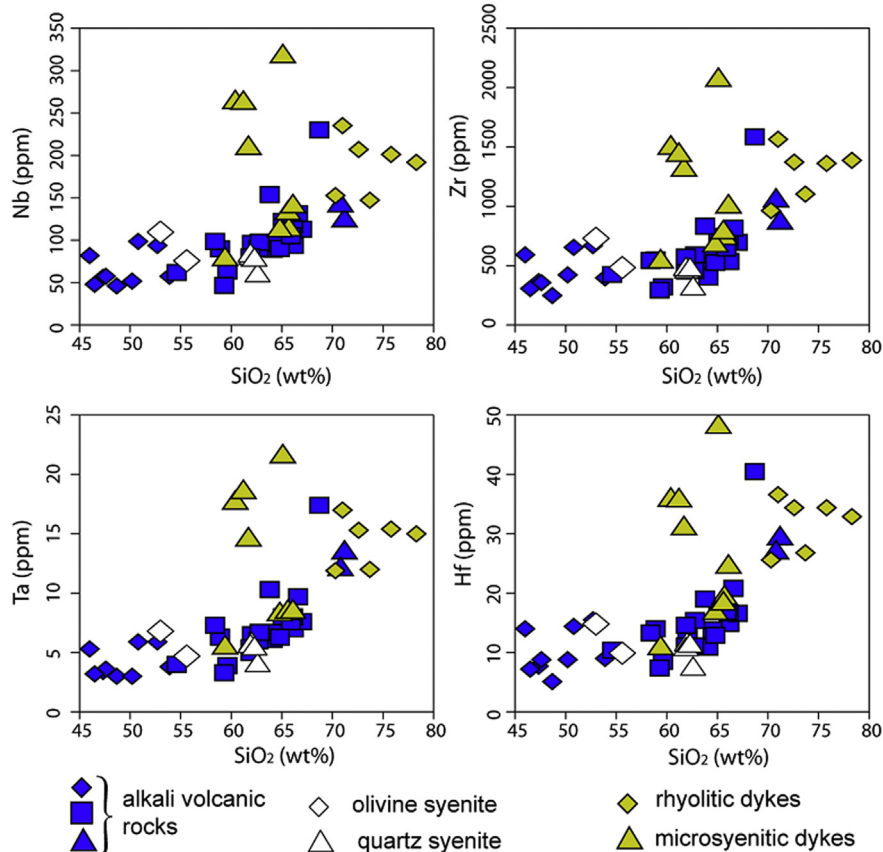


Fig. 11. Plot of selected HFSE versus SiO₂. Note that the volcanic rocks generally follow a trend of increasing HFSE with increasing silica above around 60 wt% SiO₂ while the late dykes are less systematic in their variations.

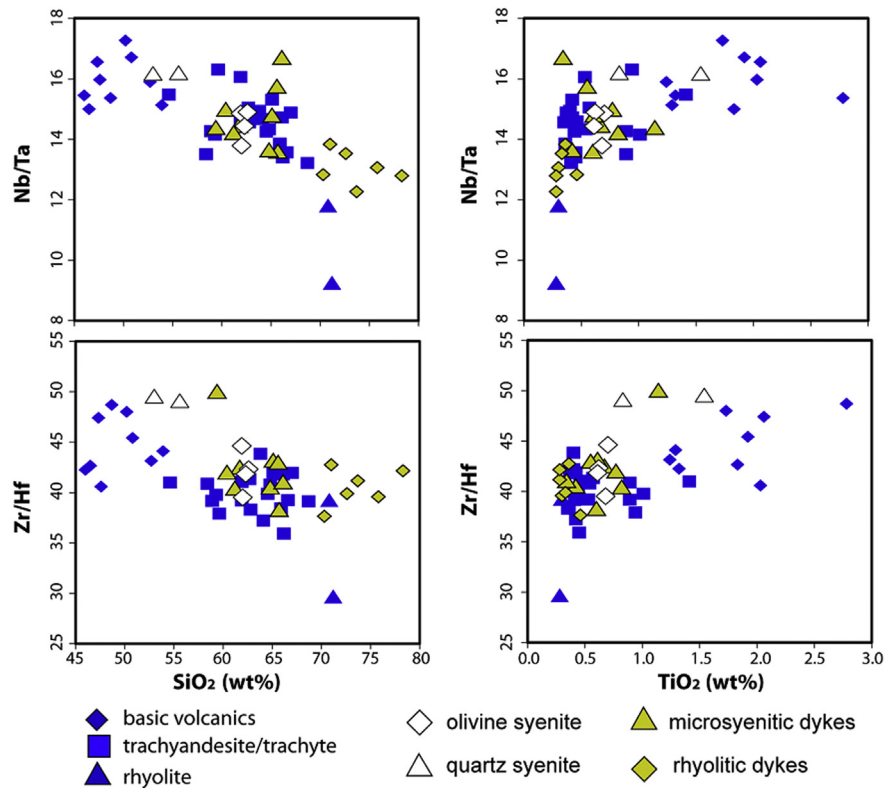


Fig. 12. Plot of Nb/Ta and Zr/Hf ratios versus SiO_2 and TiO_2 to evaluate the relationships between the different magmatic rock types of Jbel Boho. Note that the progression from basic to silica-rich lithologies seen in the volcanic rocks corresponds to a stratigraphic sequence.

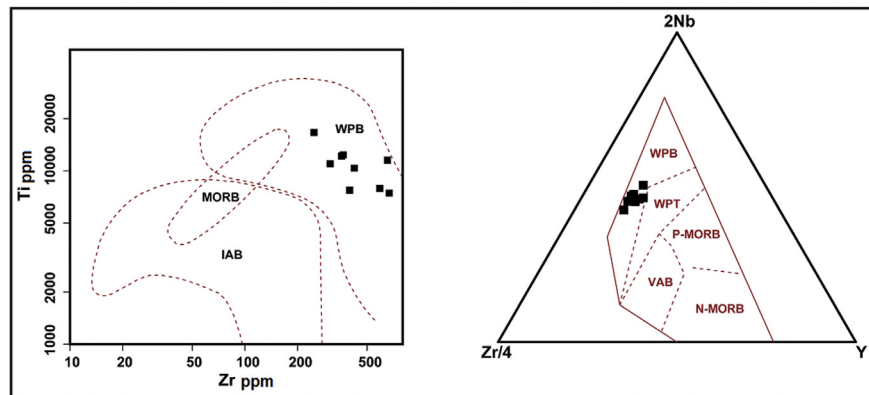


Fig. 13. Tectonic discrimination diagrams for the Jbel Boho basalts, showing their intraplate magmatic affinity. Ti–Zr plot after Pearce (1982) and Zr/4–2Nb–Y plot after Meschede (1986). WPB (within plate basalt), WPT (within plate tholeiite), IAB (island arc basalt), VAB (volcanic arc basalt), MORB (mid ocean ridge basalt), N-MORB (normal MORB), P-MORB (plume MORB).

The intrusion of the microsyenitic dykes (with trachyandesitic to trachytic compositions), which followed the volcanic rock suite, marks a change to less differentiated magma with higher contents of compatible elements (see hacker diagram, Fig. 9, e.g. MgO , CaO , TiO_2 , Al_2O_3) and significant variation in HFSE contents at similar SiO_2 contents (Fig. 11) in comparison with the most differentiated rhyolitic lavas that represent the last differentiation stage of the volcanic rocks. In addition, the REE compositions of the dykes were normalized to the last differentiated lavas (rhyolite B88-2, Fig. 16) to show the variation of their REE signatures with respect to volcanic rocks that have similar REE patterns. The normalized REE patterns clearly show that most dykes are REE-depleted in comparison to the differentiated lavas and all dykes show positive Eu

anomalies. Therefore, the change from the volcanic suite to the dyke suite cannot be explained by the effects of crystal fractionation from the same magma. Thus, we deduce that these dykes are derived from a third generation of melt.

Overall the trace elements patterns of the volcanic suite and the dyke suite (Fig. 14) are similar, but not identical. The similarities suggest that they have a similar source, but the differences require different processes in the crust. In the volcanic suite, both the gradual increase of the HFSE with increasing SiO_2 contents and REE patterns displaying an increasingly negative Eu anomaly with increasing REE contents, suggest they evolved mainly by fractional crystallization of feldspar. On the other hand, the dyke suite shows varying negative Eu anomalies and strongly varying HFSE contents

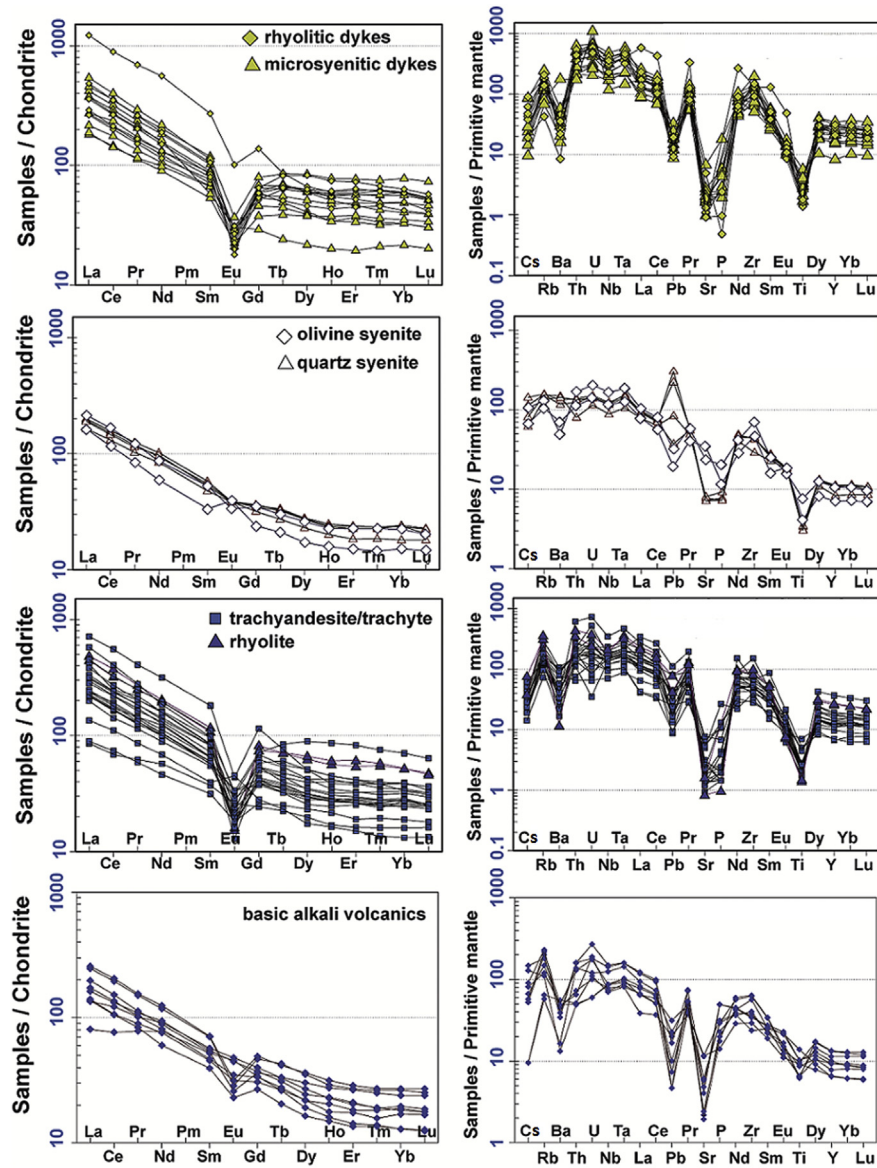


Fig. 14. The REE (left column) and other trace elements pattern (right column) of the Jbel Boho igneous complex normalized to chondrite (Boynton, 1984) and primitive mantle (McDonough and Sun, 1995). The diagrams represent, from bottom to top, the relative chronology (from young to old) of the Jbel Boho rocks.

Table 6

Representative microprobe analyses of olivine in the Jbel Boho olivine syenite.

Olivine analyses of the olivine syenite (B10)											
	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	34.38	34.31	34.18	34.12	34.10	34.04	34.20	33.81	33.96	33.36	33.90
FeO	45.31	45.59	45.88	47.09	47.12	48.11	48.08	48.98	48.74	49.13	50.18
MnO	1.90	1.84	1.90	2.03	1.97	2.05	2.11	2.02	2.18	2.08	2.17
MgO	19.10	18.37	18.11	17.13	17.11	16.28	15.97	15.80	15.37	15.55	13.81
Total	100.69	100.11	100.07	100.37	100.30	100.48	100.36	100.61	100.25	100.12	100.06
Number of ions based on 4 O											
Si	1.01	1.01	1.01	1.01	1.01	1.01	1.02	1.01	1.02	1.01	1.03
Fe ²⁺	1.11	1.12	1.13	1.17	1.17	1.20	1.20	1.22	1.22	1.24	1.27
Mn	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.05	0.06
Mg	0.83	0.81	0.80	0.76	0.76	0.72	0.71	0.70	0.69	0.70	0.62
Endmember proportions											
Fo	41.89	40.83	40.31	38.33	38.31	36.64	36.18	35.57	34.97	35.11	31.98
Fa	55.74	56.84	57.28	59.09	59.18	60.74	61.10	61.85	62.21	62.22	65.17
Tp	2.37	2.32	2.40	2.58	2.51	2.62	2.72	2.58	2.82	2.67	2.85

Table 7
Representative microprobe analyses of amphiboles of the two syenite types from Jbel Boho.

	Amphiboles from quartz syenite (B48-3)									Amphiboles from olivine syenite (B10)				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO ₂	49.05	48.74	47.95	49.05	50.37	50.55	49.28	50.14	49.33	42.28	41.84	41.86	41.51	41.68
TiO ₂	1.08	2.43	3.07	1.99	0.35	0.37	0.32	0.23	0.48	2.85	2.90	2.99	3.12	3.14
Al ₂ O ₃	0.77	1.19	1.12	0.87	0.34	0.36	0.40	0.41	0.43	9.70	9.67	9.83	10.04	10.03
FeO	32.14	29.01	30.75	31.46	34.84	34.76	34.77	34.22	34.84	16.61	17.95	17.19	17.49	16.78
MnO	1.21	0.91	1.08	1.07	1.48	1.50	1.36	1.41	1.37	0.43	0.43	0.45	0.46	0.52
MgO	1.57	3.35	1.47	1.76	0.30	0.36	0.45	0.59	0.40	10.28	9.37	9.90	9.58	9.85
CaO	4.06	5.01	4.61	4.36	1.09	1.96	2.32	2.69	2.32	11.03	11.04	10.83	11.03	11.13
Na ₂ O	6.59	6.11	6.25	6.28	7.92	7.54	7.15	7.01	7.32	3.02	3.00	3.11	2.94	2.97
K ₂ O	1.37	1.52	1.46	1.48	1.31	1.34	1.43	1.44	1.39	1.80	1.83	1.78	1.84	1.76
Total	97.83	98.27	97.76	98.33	98.00	98.74	97.47	98.14	97.87	98.03	98.05	97.95	98.01	97.86
Number of ions based on 23 O														
Si	7.87	7.70	7.70	7.82	8.00	8.00	7.92	8.00	7.91	6.42	6.40	6.38	6.34	6.35
Al	0.13	0.22	0.21	0.16	0.00	0.00	0.08	0.00	0.08	1.58	1.60	1.62	1.66	1.65
Total	8.00	7.92	7.91	7.99	8.00	8.00	8.00	8.00	7.99	8.00	8.00	8.00	8.00	8.00
Al	0.02	0.00	0.00	0.00	0.06	0.07	0.00	0.08	0.00	0.16	0.14	0.15	0.15	0.15
Ti	0.13	0.29	0.37	0.24	0.04	0.04	0.04	0.03	0.06	0.33	0.33	0.34	0.36	0.36
Fe	4.31	3.83	4.13	4.20	4.63	4.60	4.67	4.57	4.67	2.11	2.30	2.19	2.23	2.14
Mn	0.16	0.12	0.15	0.14	0.20	0.20	0.19	0.19	0.19	0.06	0.06	0.06	0.06	0.07
Mg	0.37	0.79	0.35	0.42	0.07	0.08	0.11	0.14	0.10	2.33	2.14	2.25	2.18	2.24
Total	5.00	5.03	5.00	5.00	5.00	5.00	5.00	5.00	5.01	4.97	4.96	4.99	4.98	4.96
Ca	0.70	0.85	0.79	0.75	0.19	0.33	0.40	0.46	0.40	1.79	1.81	1.77	1.80	1.82
Na	2.05	1.87	1.95	1.94	2.44	2.31	2.23	2.17	2.28	0.89	0.89	0.92	0.87	0.88
K	0.28	0.31	0.30	0.30	0.27	0.27	0.29	0.29	0.28	0.35	0.36	0.35	0.36	0.34
Total	3.03	3.03	3.04	2.99	2.89	2.92	2.92	2.92	2.96	3.03	3.06	3.03	3.03	3.04
Mg/(Mg+Fe ₂)	0.08	0.17	0.08	0.09	0.02	0.02	0.03	0.03	0.02	0.52	0.48	0.51	0.49	0.51

Table 8
Representative microprobe analyses of clinopyroxene in the olivine syenite from Jbel Boho.

	Pyroxene analyses from olivine syenite (B10)											
	1	2	3	4	5	6	7	8	9	10	11	12
SiO ₂	50.92	51.15	51.22	51.42	51.46	50.56	51.25	51.19	51.20	50.21	51.35	51.31
TiO ₂	0.94	0.89	0.89	0.95	0.80	1.35	1.00	0.83	0.85	1.65	1.16	1.07
Al ₂ O ₃	2.14	2.07	1.88	2.29	1.85	2.89	2.13	2.02	1.93	3.48	2.41	2.38
FeO	11.57	11.56	11.58	9.69	11.80	9.77	11.08	11.09	10.76	9.68	8.93	8.99
MnO	0.50	0.48	0.42	0.43	0.55	0.45	0.42	0.45	0.45	0.40	0.38	0.40
MgO	11.26	11.19	11.19	12.34	10.84	11.99	11.19	11.26	11.32	11.52	12.43	12.61
CaO	21.99	21.80	21.67	22.09	21.80	22.10	21.98	22.21	22.11	22.09	22.52	22.45
Na ₂ O	0.72	0.74	1.06	0.75	0.75	0.81	0.86	0.83	0.81	0.83	0.76	0.73
Total	100.04	99.89	99.91	99.96	99.85	99.92	99.91	99.88	99.43	99.86	99.94	99.94
Numer of ions based on 6 O												
Si	1.93	1.94	1.94	1.93	1.95	1.91	1.94	1.94	1.95	1.89	1.93	1.93
Ti	0.03	0.03	0.03	0.03	0.02	0.04	0.03	0.02	0.02	0.05	0.03	0.03
Al	0.10	0.09	0.08	0.10	0.08	0.13	0.10	0.09	0.09	0.15	0.11	0.11
Fe ²⁺	0.37	0.37	0.37	0.30	0.37	0.31	0.35	0.35	0.34	0.31	0.28	0.28
Mn	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mg	0.64	0.63	0.63	0.69	0.61	0.67	0.63	0.64	0.64	0.65	0.70	0.71
Ca	0.89	0.89	0.88	0.89	0.89	0.89	0.89	0.90	0.90	0.89	0.91	0.90
Na	0.05	0.05	0.08	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05
Mg/(Mg+Fe ²⁺)	0.63	0.63	0.63	0.69	0.62	0.69	0.64	0.64	0.65	0.68	0.71	0.71
Endmember proportions												
En	34.68	34.36	35.17	37.64	33.20	37.18	34.54	34.83	34.93	35.85	37.85	38.40
Fs	16.63	17.53	15.87	13.93	18.82	13.56	16.71	15.79	16.03	14.74	12.87	12.46
Wo	48.68	48.11	48.96	48.43	47.98	49.26	48.76	49.38	49.04	49.41	49.28	49.14

at similar SiO₂ contents for the microsyenites (Fig. 11). This cannot be explained by only fractional crystallization (FC). In addition to FC, assimilation of crustal components (AFC) or magma recharge, which should be tested by further studies as well as late hydrothermal fluid impregnation, may explain this unusual trace element features.

The subalkaline character of the rhyolitic dykes as suggested by their position in the TAS diagram seems to contrast with the alkaline nature of the complex (Fig. 8) and might therefore be related to new magma generation that is derived from higher degree of melting. However they share more similarities of

incompatible element signatures with the alkaline rocks. Therefore, the subalkalinity should not be taken as a strong argument for a new magma generation as the fluid immobile trace elements (Zr/Ti vs. Nb/Y; Fig. 10) indicate also an alkaline character of the rhyolitic dykes suggesting that fractionation of alkali elements would have occurred during differentiation or that their low alkaline content might be a fluid-induced secondary feature.

The very high SiO₂ contents in the rhyolitic dykes suggest they might represent the final stage of the magmatic evolution in Jbel Boho, as magma cooled and fractionation proceeded to solidification.

Table 9

Chemical analyses for synchysite from the REE enriched rhyolitic dyke (B35) of Jbel Boho complex. Ionic formulae calculated based on 7 oxygens following Guastoni et al. (2009).

Synchysite analyses of the rhyolitic dyke (B35)													
	1	2	3	4	5	6	7	8	9	10	11	12	average
F	4.07	5.41	5.23	5.01	4.75	4.71	5.09	4.71	4.42	4.67	5.59	5.66	4.94
CaO	18.76	18.37	18.40	18.74	18.78	18.75	18.39	18.64	18.88	18.89	18.29	18.05	18.58
La ₂ O ₃	12.25	12.67	12.25	11.96	12.50	13.16	13.61	13.11	12.30	12.25	12.21	12.15	12.53
Ce ₂ O ₃	20.03	19.66	20.92	19.65	19.83	20.19	20.83	20.92	20.55	20.61	20.92	20.07	20.35
Pr ₂ O ₃	3.04	2.67	2.84	2.64	2.90	2.87	2.72	2.75	2.75	2.72	3.19	2.77	2.82
Nd ₂ O ₃	11.49	10.61	11.33	11.05	10.60	9.69	9.66	9.81	10.59	11.00	10.42	10.97	10.60
Sm ₂ O ₃	1.54	1.58	1.36	1.68	1.29	1.24	1.25	1.37	1.40	1.62	1.39	1.34	1.42
Eu ₂ O ₃	0.18	0.20	0.00	0.01	0.00	0.31	0.17	0.18	0.00	0.00	0.00	0.06	0.09
Gd ₂ O ₃	1.25	1.10	0.61	1.34	1.21	0.95	0.78	0.81	1.09	1.19	0.83	1.16	1.03
Dy ₂ O ₃	0.00	0.03	0.00	0.00	0.00	0.07	0.04	0.02	0.00	0.00	0.00	0.00	0.01
Y ₂ O ₃	0.52	0.35	0.15	0.49	0.50	0.71	0.55	0.37	0.19	0.29	0.23	0.35	0.39
Er ₂ O ₃	0.05	0.00	0.02	0.00	0.00	0.05	0.04	0.00	0.00	0.00	0.00	0.02	0.02
Yb ₂ O ₃	0.11	0.00	0.00	0.03	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01
ThO ₂	0.07	0.06	0.37	0.00	0.41	0.00	0.00	0.00	0.09	0.14	0.33	0.38	0.16
CO ₂	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50
Sum	99.86	99.20	100.00	99.10	99.26	99.22	99.63	99.19	98.76	99.86	99.91	99.49	99.46
F ₂ O	1.71	2.28	2.20	2.11	2.00	1.98	2.14	1.98	1.86	1.96	2.35	2.38	2.08
Total	98.15	96.92	97.80	96.99	97.26	97.23	97.49	97.20	96.90	97.90	97.56	97.11	97.37
Number of ions based on 7 O													
F	0.71	0.94	0.91	0.87	0.83	0.82	0.88	0.82	0.77	0.81	0.97	0.98	0.86
Ca	1.11	1.08	1.08	1.11	1.11	1.11	1.08	1.10	1.12	1.11	1.07	1.06	1.09
La	0.25	0.26	0.25	0.24	0.25	0.27	0.28	0.27	0.25	0.25	0.25	0.25	0.25
Ce	0.41	0.40	0.42	0.40	0.40	0.41	0.42	0.42	0.42	0.42	0.42	0.40	0.41
Pr	0.06	0.05	0.06	0.05	0.06	0.06	0.05	0.06	0.06	0.05	0.06	0.06	0.06
Nd	0.23	0.21	0.22	0.22	0.21	0.19	0.19	0.19	0.21	0.22	0.20	0.22	0.21
Sm	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03
Eu	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gd	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02
Dy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Y	0.02	0.01	0.00	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
Er	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Th	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	2.00	1.99	1.99	1.99	2.00	2.00	1.99	2.00	2.01	1.99	1.98	1.99	1.99
ΣREE + Th: 0.99													
Ca: 1.09			F: 0.86			C: 1.99							

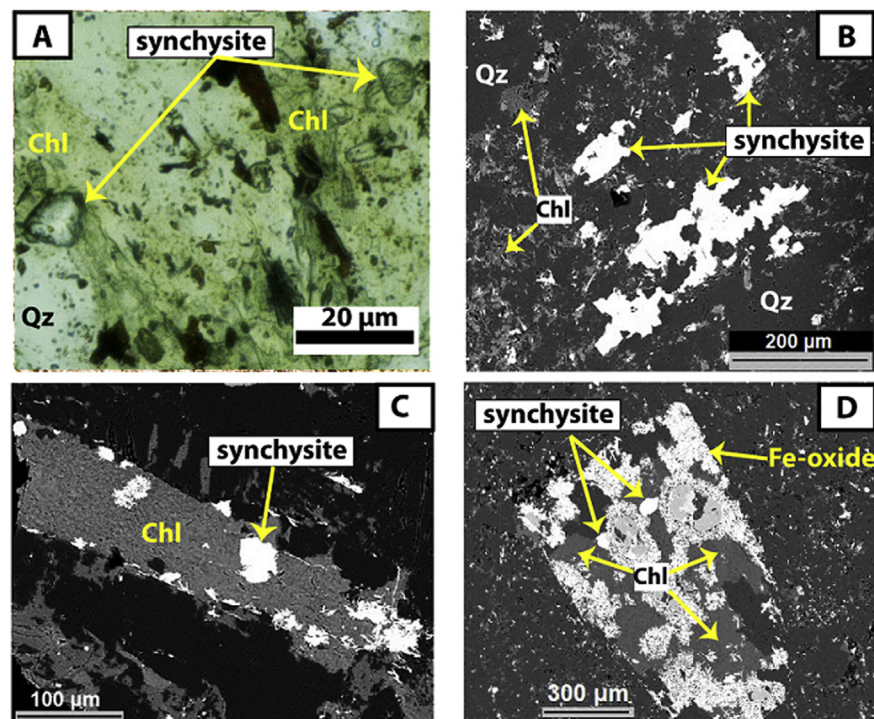


Fig. 15. Typical synchysite occurrences in the LREE-enriched rhyolitic dyke B35. A LPL Photo-micrograph shows small anhedral synchysite grains (up to 20 μm) in a quartz-rich groundmass. B Backscattered electron micrograph of anhedral synchysite (up to 300 μm) associated with quartz and chlorite. C Backscattered electron micrograph of synchysite within chlorite. D Backscattered electron micrograph of synchysite associated with chlorite in an Fe-oxide grain.

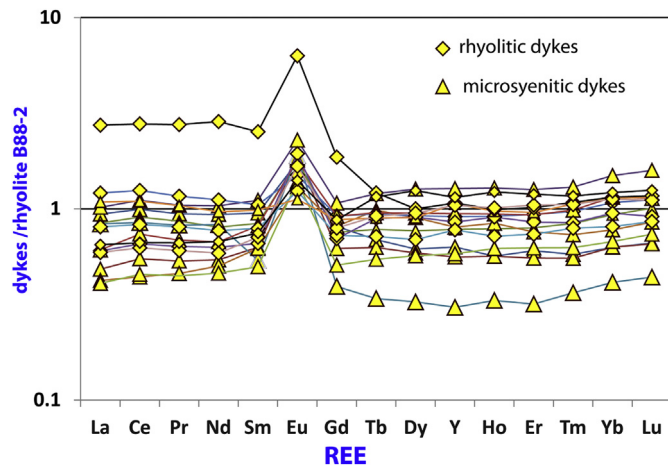


Fig. 16. REE plot of the dyke suite normalized to rhyolite (B88-2) showing the variation of REE signatures of the late intrusive dykes with respect to the late differentiated lava of the volcanic suite.

7.2. HFSE fractionation during differentiation

Differences in absolute element concentrations (e.g. in the HFSE in the microsyenitic dykes, see Fig. 11) suggests that differing degrees of partial melting or paths of fractional crystallization or crustal contamination have been followed by the various magma batches identified above once they left this source.

We see evidence at Jbel Boho for fractionation taking place under unusual conditions, leading for example to negative correlations between ratios of similarly incompatible elements such as Nb/Ta and an index of fractionation like SiO_2 (Fig. 12). Although the fractionation of Nb–Ta and Zr–Hf pairs could be a result of the fractional crystallization of Ti bearing phases like rutile, titanite and ilmenite (Chen and Zheng, 2015; Claiborne et al., 2006; John et al., 2011; Linnen and Keppler, 2002; Marks et al., 2008; Pfänder et al., 2007), a positive correlation exists between TiO_2 and Nb/Ta or Zr/Hf (Fig. 13). $D_{\text{Nb/Ta}}$ and $D_{\text{Zr/Hf}}$ in rutile and ilmenite are less than 1 (Green and Pearson, 1987; Mallmann et al., 2014; Pfänder et al., 2007), and the fractionation of such minerals would increase these ratios in the melt, which is the opposite to what is observed. In addition, we see a positive correlation between fractionation indices and absolute concentrations of HFSE even in the most evolved volcanic rocks, which argues against the fractionation of zircon or other HFSE bearing phases playing a significant role. Some authors (Hui et al., 2011; Niu, 2012) proposed the process of “mass-dependent fractionation during magmatism” to explain Nb–Ta and Zr–Hf fractionation in magmatic systems. They suggest that the lighter elements $^{90-96}\text{Zr}$ and ^{93}Nb would behave more incompatible than the heavier elements $^{174-180}\text{Hf}$ and ^{181}Ta in magmatic processes. In terms of crystal fractionation, this should lead to Zr/Hf and Nb/Ta ratios increasing in the melt as fractionation proceeds. This is again opposite of what is observed (Fig. 12). This indicates that neither mineral fractionation nor mass-dependent fractionation can explain the fractionation of these HFS elemental twins in the Jbel Boho volcanic rocks. Hence, a different process must have been involved.

Dostal and Chatterjee (2000) and Green (1995) proposed that fluid fractionation and the addition of mineralizing fluids could fractionate Ta and Nb with preference for Ta in the fluids. Fluorine could play an important role in the form of F^- to facilitate the transport of the HFSE in the magma and the hydrothermal fluids, forming HFSE–F complexes which could lead to high enrichment of some HFSE (Agangi et al., 2010; Demartis et al., 2014; Sheard et al.,

2012; Timofeev et al., 2015). Alkaline magmatic rocks are generally enriched in volatiles, and the evidence from fluorite inclusions and from fluorine-containing secondary minerals such as fluorite and synchysite at Jbel Boho suggests that fluorine may be an important volatile component that triggered the observed HFSE fractionation in the evolved rocks.

7.3. Syenite petrogenesis

The Jbel Boho syenites, which are particularly distinctive in the Jbel Boho context due to the lack of strong negative Eu anomalies, seem unlikely to be produced by fractional crystallization of magma from a mantle source. The present data do not allow us to clearly determine the petrogenesis of these syenites. However, we can discuss the petrogenesis of the Jbel Boho syenites in context of existing models.

Yang et al. (2012, 2008, 2005) discuss three main petrogenetic models for the formation of syenitic rocks: 1) extensive fractional crystallization of mantle derived melts, 2) magma mixing processes of mantle-derived undersaturated alkaline magma with crustal-derived silicic melts, and 3) partial melting of underplated crustal rocks. The absence of negative Eu anomalies in the Jbel Boho syenites argues against the first model, as extensive fractional crystallization would lead to the formation of evolved rocks with strong negative Eu anomalies. The second model was proposed by Yang et al. (2012, 2008) to explain the occurrence of syenitic intrusions without negative Eu anomalies in the eastern and northern North China Craton. However it is not fully understood why magma mixing processes should lead to highly evolved rocks without negative Eu anomalies. Markl (2001) suggested that varying Eu anomalies could be the result of mixing of plagioclase cumulates (positive Eu-anomalies) with residual magmas with pronounced negative anomalies, although at Jbel Boho no correlation is seen between Eu/Eu^* and indices of fractionation such as SiO_2 that this process should produce. Partial melting of underplated mafic cumulate rocks appears to be the most likely model to explain the formation of the Jbel Boho syenitic pluton, but has to be tested by further studies. The absence of distinct negative Eu anomalies in highly evolved rocks like syenites which are presumably derived from more mafic compositions by crystal fractionation implies that the mafic precursors must have had high Eu contents. Mafic rocks with some cumulate plagioclase, representing a reservoir for Eu would produce melts that are Eu-enriched (Shellnutt and Iizuka, 2012; Shellnutt and Zhou, 2008, 2007). These authors have explained the petrogenesis of fayalite syenite in the Panxi region SW of China, which has a very similar composition and REE pattern to the Jbel Boho olivine syenite, by this melting model. Moreover, Shellnutt and Iizuka (2012) have attributed the formation of such syenites to melting under relatively oxidizing conditions ($f\text{O}_2 > \text{FMQ}$), which will produce a preference for Eu^{3+} over Eu^{2+} that precludes fractionation of Eu over the other REE by feldspar.

Because crustal rocks typically have higher contents of Pb than mafic magmas (Rudnick and Fountain, 1995), the presence of significant positive Pb anomalies in the quartz-syenite (in primitive mantle normalized trace element patterns, Fig. 14) and its elevated SiO_2 argue for the influence of crustal contamination of the syenitic magma. Consequently, the composition of the quartz syenite is probably of secondary origin.

7.4. REE enrichment and the role of hydrothermal fluids

Alkaline igneous rocks form by low degree partial melting of the mantle and are therefore highly enriched in incompatible elements such alkali elements, REE, Zr, Ba and Nb. As the LREE are more incompatible than the HREE, they are in the resulting melts always

highly enriched relative to the HREE. The REE contents in the melt tend therefore to increase with increasing magma differentiation with more preference of LREE over the HREE, which is obviously seen as expected in the REE patterns of the Jbel Boho magmatic rocks (Fig. 14).

The Σ LREE contents in the dykes range from 252 ppm to 678 ppm. Unusually strong LREE enrichment (Σ LREE = 1750 ppm) is found in one rhyolitic dyke B35 (Fig. 14, pattern with the highest LREE concentrations). This very high LREE content is associated with the presence of the REE–F–Ca carbonate synchysite, which occurs as tiny anhedral to subhedral crystals (up to 30 μ m) and as much bigger anhedral and altered minerals (up to 300 μ m) together with quartz and chlorite within the groundmass or in pseudomorphs associated with chlorite and Fe-oxides (e.g. Fig. 15A–D). This dyke (B35) is, with the exception of its LREE enrichment, chemically very similar to the other dykes, falling on the same trends in both major (Fig. 8) and trace (Fig. 12) element diagrams. This suggests that processes of partial melting or fractional crystallization are not alone responsible for its extreme LREE enrichments. Evidence of fluid effect that might have caused the high LREE contents is reflected by tiny carbonate and quartz veins (in addition to the groundmass crystals) within the dyke (Fig. 7H,G). Furthermore, strong feldspar albitization and the common association of the REE–Ca–F carbonate synchysite with chlorite and Fe-oxides (which may form pseudomorphs after primary Fe–Mg minerals) argue for late hydrothermal fluid impregnation. This suggests that the rare earth mineralization originates most likely from the influence of REE-rich hydrothermal fluids.

Recent experimental studies have further shown that LREE-chloride complexes are highly mobile in hydrothermal fluids at acidic conditions and high ligand (e.g. Cl and F) activity (Migdisov et al., 2009; Williams-Jones et al., 2012; Williams-Jones and Migdisov, 2014). Based on these experimental studies, the mineralization model we propose for Jbel Boho consists of the transport of REE as chloride complexes at acidic hydrothermal fluid conditions in the presence of F as the analysed synchysite contains F and fluorite is present in many samples. These low pH fluids may create pathways in the host-rock by provoking acidic alteration. The REE will be precipitated from the fluids when their pH rises. In the case of Jbel Boho, carbonate and feldspar are available for the neutralization of the fluids as they cause the pH of the solution to rise. The carbonates probably also provided the CO_3^{2-} and Ca^{2+} needed for the formation of synchysite. Similar REE mineralization model have also been suggested in the formation of some pegmatite REE deposits (Gysi and Williams-Jones, 2013).

The presence of synchysite also in the fine grained groundmass in the dykes in addition to the small veins may indicate that the REE rich hydrothermal fluids came already in contact with the dyke melt at subsolidus conditions.

7.5. Regional implications

In addition to the REE mineralization in Jbel Boho, the Precambrian–Cambrian transition is characterized by widespread metallogenic and hydrothermal activity, which represents a crucial period in the evolution of the WAC. Indeed critical turning in the earth evolution such as lithospheric delamination and thinning, uplift and anorogenic magmatism were recorded (Doblas et al., 2002). Some important metallogenic activities during this period are represented by the copper deposits of Jbel Laassel within early Cambrian dolomite in the Bou Azzer inlier (30 km NE of Bleida) (Bourque et al., 2015). The interlayered volcanic rocks belong to the Jbel Boho formation, which suggest the influence of such magmatic activities as source of such mineralization. Some deposits like the Imiter silver deposits in the Anti-Atlas (Saghro) are associated with

calc-alkaline granodioritic magmatism during the late Ediacaran magmatism of the Ouarzazate Group (Cheilletz et al., 2002; Levresse et al., 2016).

In the Oulad Dlim massif of the southern part of Morocco (Fig. 1) Bea et al. (2015) reported new evidences for REE- and HFSE-rich peralkaline granitic intrusions (~525 Ma), which they attribute to the Cambrian rifting event. Other important REE ore deposits, which were recently discovered in the Oulad Dlim massif associated with carbonatite bodies of different times may host a world-class deposits of REE, Nb and U (Montero et al., 2016; ONHYM, 2016a, 2016b).

8. Conclusion

The Jbel Boho alkaline complex contains some of the best preserved magmatic rocks produced during an event marking the transition from Neoproterozoic to Cambrian in the Anti-Atlas. It was formed after the emplacement of the Bou Azzer ophiolite and the volcanoclastic rocks of the Ouarzazate Group under shallow marine conditions in an extensional tectonic regime south of the AAMF along the northern edge of the WAC.

The magmatic evolution of the Jbel Boho alkaline complex is characterized by three magma generations, which have experienced different petrogenetic processes. 1) The first magma generation produced a suite of volcanic rocks evolving in time from primitive basanites/tephrites to trachytes and eventually rhyolites by fractional crystallization. 2) The second magma generation led to the formation of the syenitic pluton. The composition of the two syenite types (olivine syenite and quartz syenite) including high alkali contents, the absence of negative Eu anomalies and a new mineral assemblage with fayalite, Ca-pyroxene, hornblende and arfvedsonite suggests they were produced by partial melting of mafic cumulates at deep crustal levels. In addition, the occurrence of quartz and a positive Pb in the quartz syenite suggests that this magma was affected by crustal contamination. 3) The magmas of the later dyke swarm (microsyenitic and rhyolitic dykes) show the presence of plagioclase in some microsyenitic dykes contrasting with its general absence in either the syenites or the most evolved volcanic rocks. In addition, the trachyandesitic to trachytic compositions of the microsyenitic dykes marks a change to less differentiated rocks with respect to the most differentiated volcanic rocks (rhyolite). This and their strongly differing high field-strength element contents suggest they are derived from a third batch of magma.

Negative correlations between ratios such as Nb/Ta and Zr/Hf (which should not normally be affected by crystal fractionation) and SiO_2 suggest that element fractionation processes involving complexation, perhaps by F, played a petrogenetic role in many of the magmas. That the magmas were F-rich is attested to by the presence of fluorite both in the groundmass of a trachyte and as inclusions in the Na-amphibole of the rhyolitic lavas as well as the presence of REE–F–Ca carbonate synchysite–(Ce) in some of the late, REE-enriched rhyolite dykes.

Synchysite–(Ce) is the unique REE mineral identified by EPMA analysis in a rhyolitic dyke with strong LREE enrichment (Σ LREE = 1750 ppm). This unusually high LREE content probably does not only reflect a magmatic signature, but is also the result of interacting REE-rich hydrothermal fluid in the presence of F, Cl, Ca and CO_3 , that came into contact with the dyke may be at subsolidus conditions. Such highly-fractionated intrusive rocks in alkaline complexes are good prospects for REE mineralization.

The Jbel Boho alkaline magmas show clear within-plate geochemical signatures. This implies that the major tectonic change from a compressive to an extensional setting, which started with the volcano-clastic series of the Ediacaran Ouarzazate Group

after the ophiolite emplacement, continued during the early Cambrian.

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