Geochemistry of arc volcanic rocks of the Zagros Crush Zone, Neyriz, Iran

H.A. Babaiea,*, A.M. Ghazi a, A. Babaei b, T.E. La Tour a, A.A. Hassanipak c

aDepartment of Geology, Georgia State University, Atlanta, GA 30303, USA
bDepartment of Biology, Geology, and Environmental Sciences, Cleveland State University, Cleveland, Ohio, USA
cDepartment of Mining Engineering, University of Tehran, Tehran, Iran

Abstract

The northeastern margin of the Tethyan Neyriz ophiolite complex in southwestern Iran is tectonically juxtaposed under cataclastically-deformed island arc volcanic–volcaniclastic rocks. We document this arc component of the Zagros Crush Zone in the Neyriz area, and describe its petrographic and geochemical characteristics. The arc unit which we call the Hassanabad Unit, is tectonically intercalated with Cretaceous limestone in the cataclastic shear zone around the Hassanabad pass north of Neyriz.

Analyses of the distributions of the major, rare earth and other trace elements in the volcanic rocks of the Hassanabad Unit reveal a dominantly calc-alkaline island arc composition. Volcanogenic sandstone and sedimentary breccia, with clasts of basalt, andesite and diorite, are cataclastically intercalated with pillowed calc-alkaline island arc volcanic rocks, pelagic limestone and radiolarian chert. Trace element geochemistry corroborates the petrographic evidence that the poorly-sorted and angular volcanogenic sediments were derived locally from the island arc volcanic and intrusive rocks. The emplacement of the volcanic arc rocks adjacent to the thrust sheets of the crustal and mantle sequences of the Neyriz ophiolite was probably a result of subduction-related processes during closure of the Tethys ocean during the Late Cretaceous.

q 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Rare earth and other relatively immobile trace elements are useful to elucidate the probable tectonic setting of eruption of basalt and other volcanic rocks in ophiolites (Pearce and Cann, 1973; Shervais, 1982; Meschede, 1986; Dudás, 1992; Pearce, 1987, 1996).

The geochemistry and petrology of some lavas in the large and well preserved Tethyan ophiolites of Troodos (Cyprus) and Semail (Oman) are significantly different from the oceanic crust that forms at mid oceanic ridge centers (Serri, 1981; Moores, 1982; Bloomer and Hawkins, 1983; Rautenschlein et al., 1985; Coleman, 1984; Pearce et al., 1984; Leith, 1984). These ophiolitic lavas have trace element geochemical systematics that relate more to subduction zone processes than those along mid ocean ridges (Leith, 1984; Bloomer et al., 1995; Kerrich and Wyman, 1996). Pearce et al. (1984) and Rautenschlein et al. (1985), studying lavas in the Semail ophiolite in Oman and Troodos ophiolite in Cyprus, respectively, have documented a subduction zone trace element geochemical signature for these Tethyan ophiolites that are of the same age and paleo-geodynamic setting as those of the Neyriz ophiolite in Iran — the subject of this paper. The field and geochemical work of Alabaster et al. (1980, 1982), Pearce et al. (1981) and Pearce (1982), have revealed that part of the Oman ophiolite complex consists of backarc oceanic crust intruded by products of volcanic arc magmatism.

The Neyriz ophiolite is one of several large allochthonous Tethyan ophiolites that are exposed in the southwestern edge of the NW–SE-trending Sanandaj–Sirjan belt, north-east of the Zagros fold-and-thrust belt in Iran (Ricou, 1971b; Gansser, 1974; Stocklin, 1968, 1977; Stoneley 1981, 1990). Although a paleo-subduction zone has been hypothesized to exist between the Neyriz ophiolite and the Sanandaj–Sirjan belt (Haynes and McQuillan, 1974; Pilger and Rössler,1976; Adib et al., 1977; Alavi, 1980), no arc-related volcanic rocks have been documented previously in this area. Desmons and Beccaluva (1983) report arc lavas in the Sahneh ophiolite (near Kermanshah) — which is tectonically and temporally related to the Neyriz ophiolite — about 600 km to the northwest of Neyriz.

In this paper, we analyze the distribution of immobile trace elements, including the rare earth elements, in volcanic and volcaniclastic rocks of the Zagros Crush Zone immediately to the northeast of the Neyriz ophiolite complex. We show that these rocks have a subduction zone geochemical signature and probably represent a volcanic arc within the Neo-Tethys basin.
2. Tectonostratigraphy and geologic history of the Neyriz area

The Neyriz ophiolite complex is part of the “Croissant Ophiolitique” (Ricou, 1971b, 1976) that stretches between Oman and the Mediterranean (Gansser, 1974; Stocklin, 1968, 1977; Coleman, 1981; Moores, 1982; Moores et al., 1984; Stoneley, 1990). The term Neyriz ophiolite complex, as used in this paper, represents an imbricate stack of NW-striking, NE-dipping thrust sheets of ophiolitic and related sedimentary, igneous and locally-metamorphosed rocks, exposed immediately to the southwest of the “Main Thrust” of the Zagros fold-and-thrust belt. Thrust sheets containing mantle and oceanic crustal sequences occur in the middle of the stack and constitute what we call the ophiolite component of the Neyriz ophiolite complex which includes peridotite, gabbro, diorite, plagiogranite and mafic and acidic volcanic differentiates (including mid ocean ridge basalt, MORB).

The base of the complex includes the Pichakun Series (Ricou, 1968b) which represents the abyssal facies of the Neo-Tethys ocean basin and constitutes a series of thrust sheets of late Triassic limestone, middle Jurassic oolitic and micro-brecciated limestone and middle Cretaceous conglomeratic limestone. The Pichakun Series is wedged between two thrust sheets of sheared sedimentary mélangé (e.g. Haynes and McQuillan, 1974; Pamic and Adib, 1982). The two mélangé units contain clasts of rocks of the Pichakun Series, radiolarite, pelagic limestone, ocean floor lava, Megalodon- and fusililid-bearing limestone and mylonitic metamorphic rocks such as marble, amphibolite, mica schist and serpentinite.

The contact of the lower mélange with the underlying autochthonous Sarvak Formation, exposed to the west of Lake Bakhtegan (Fig. 1), is defined by mylonitic amphibolite and represents the sole of the Neyriz ophiolite complex. The upper mélange, exposed east of the lake above the Pichakun Series, is structurally overlain by thrust sheets of the mantle and oceanic crustal sequences of the ophiolite component. Thermally metamorphosed and mylonitized carbonates are interspersed on top of the ultramafic and mafic rocks of the ophiolite component near Tang-e Hana (Ricou, 1971a; Hall, 1981; Arvin, 1982a).

The oceanic mantle and crustal sequences (the ophiolite component) were thrust onto the continental slope, trench deposits and abyssal facies, represented by the Pichakun Series and the mélange, to form the Neyriz ophiolite complex. The assembled complex was then emplaced onto the Cenomanian–Turanian shallow marine, shelf-platform carbonate facies (Sarvak Formation) at the northeastern margin of the Afro–Arabian passive continental margin (Gray, 1949; Ricou, 1968a, 1968b; Hallam, 1976; Stoneley, 1981). The sequential thrusting was due to the Late Cretaceous, NE–SW-directed contractional tectonics probably along a NE-dipping subduction zone (Stocklin, 1968; Takin, 1972; Haynes and McQuillan, 1974; Alavi, 1980, 1994; Babaie et al., 1996, 1997). The allochthonous complex occurs along the NW–SE trending “Main Thrust” zone of the Zagros Range between the Sanandaj–Sirjan belt (Haynes and McQuillan, 1974; Pilger and Rössler, 1976; Adib et al., 1977; Alavi, 1980) to the northeast and the Zagros Simply-Folded Belt to the southwest (Alavi, 1994). The Neyriz ophiolite complex is overlain unconformably by the uppermost Cretaceous anhydritic limestone of the Tarbur Formation in the east and by the Middle Eocene Jahrum Formation in the northwest (James and Wynd, 1965; Alavi, 1994).

The ophiolite complex is structurally overlain by volcanic and volcanioclastic rocks of the Hassanabad unit (the subject of this paper). The unit occurs in several variably-sized tectonic slivers which are intercalated with the Cretaceous limestone. These cataclastically-deformed rocks occur in the Zagros “Crush Zone” immediately to the northeast of the ophiolite complex.

The tectonic processes, polarity, paleogeography, timing of subduction initiation and petrogenetic setting of the subduction zone are unknown. It is generally believed that the northeastern margin of the Arabian continental margin is still subducting under the southwestern margin of the Persian segment of the Eurasian plate (i.e. below the southwestern edge of the Sanandaj–Sirjan belt), forming the Tertiary–Quaternary Central Iranian magmatic assemblage to the northeast of the Sanandaj–Sirjan belt (Berberian, 1981; Berberian and King, 1981; Kadinsky-Cade and Barzangi, 1982; Lensch et al., 1984; Snyder and Barzangi, 1986; Hempton, 1987; Alavi, 1980, 1994).

3. Background on geochemistry of Arc Magma

Island arc volcanic rocks are markedly different from MORB and ocean island basalt (OIB) in having low abundances of high field strength (HFS) elements (Ti, P, Zr, Hf, Nb, Ta) relative to the light rare earth elements (LREE) and the large ion lithophile (LIL) elements (Cs, Rb, K, Ba, Pb, Sr, Th, U; Jakes and Gill, 1970; Gorton 1977; Saunders et al., 1980; Gamble et al., 1993; Thirlwall et al., 1994; Hawkesworth et al., 1993; Pearce and Peate, 1995).

The composition of most parental volcanic arc magmas is controlled by: (i) the composition of a mantle-derived component (e.g. mantle wedge) from which they are derived under the presence of water, and which depends on the fertility of the mantle; (ii) a slab-derived fluid advection component (with high LIL/HFS and LREE/HFS elemental ratios) which depends on the temperature and amount of fluid at the slab–wedge interface; (iii) composition of the subducted plate and its sedimentary cover (e.g. Tatsumi et al., 1986; Pearce and Parkinson, 1993; Pearce and Peate, 1995). Slab-derived components may experience element fractionation and isotope exchange as fluids migrate through the mantle wedge. The frequently observed depletion of the mantle wedge
above the slab is attributed to earlier melting events (McCulloch and Gamble, 1991).

During subduction, the incompatible elements and moderately compatible LREE (e.g. La, Ce) are removed from the subducting slab by fluids or magma (Kerrich and Wyman, 1996). The subduction zone magma therefore becomes enriched in the so called non-conservative incompatible elements (i.e. those that do not remain in the slab) such as Cs, Rb, Ba, K, Pb and Sr, and to a lesser extent, the moderately non-conservative elements such as Sr, U, Th and the LREE. Tholeiitic volcanic arc basalt (TH–VAB) have negative anomalies of Nb, Zr, Ti and Y relative to the N-MORB (normal MORB), and calc-alkaline volcanic arc basalt (CA–VAB) have higher concentrations of Nb and Zr, but lower Ti and Y than the N-MORB (Pearce, 1996).

**4. Volcanic–volcaniclastic rocks of the Hassanabad Unit**

In this paper, we define a new tectonostratigraphic unit (the Hassanabad Unit) which occurs at the southwestern margin of the “Crush Zone”, immediately northeast of the Neyriz ophiolite complex. The Hassanabad Unit is designated as “vs” on Fig. 1 around and to the northwest of the Hassanabad pass on the road from Neyriz to Sirjan. It comprises pelagic sediments and volcanic and volcaniclastic rocks which are exposed as tectonic intercalations with the cataclastically-deformed Cretaceous limestone (unit “Kl” on Fig. 1) within the Crush Zone (Falcon, 1967; Wells, 1969; Haynes and McQuillan, 1974; Alavi, 1994). The Crush Zone includes both “Kl” and “vs” units on Fig. 1. The volcanic–volcaniclastic rocks of the Hassanabad Unit are part of the Cretaceous sedimentary-volcanic unit...
Fig. 2. (a) Field photograph of pillow lava in the Hassanabad Unit. Notebook and pen are for scale. (b) Photomicrograph of a micro-porphyritic volcanic rock (A10) showing a cluster of phenocrysts of partially altered plagioclase in a microlitic groundmass of small laths of plagioclase and equi-dimensional chloritized pyroxene. Image length is 1.3 mm. (c) Photomicrograph of a non-porphyritic volcanic rock (8A) with fine, prismatic plagioclase and chloritized pyroxene, and secondary epidote, calcite, quartz and chlorite. Image length is 1.3 mm. All images are in cross polarized light.
of Valeh and Alavi Tehrani (1985) and the Crush Zone of Haynes and McQuillan (1974), comprising an assemblage of pillow lava and deep water sediments such as radiolarite, red and green marl, turbiditic breccia and conglomerate. The cataclasis has involved brittle faulting which led to tectonic intercalation and brecciation of all rocks. The Cretaceous limestone extends to the Sanandaj–Sirjan block where it is relatively undeformed and lies on Precambrian basement and its cover rocks (Haynes and McQuillan, 1974).

The Sanandaj–Sirjan belt which includes metamorphic rocks, Triassic and younger volcanic–volcanioclastic rocks, continental arc intrusions and ophiolite, lies northeast of the Hassanabad Unit and southwest of the NW–SE-trending Tertiary–Quaternary Central Iranian andesitic arc volcanic belt (Stocklin, 1968; Haynes and McQuillan, 1974; Alavi, 1980).

The lavas of the Hassanabad Unit [Fig. 2(a)] are not continuous, but rather occur as tectonic lenses in shear zones, intercalated with radiolarian chert, thin limestone, mudstone and volcanogenic sandstone and sedimentary breccia. The dimensions of the cataclastic lenses vary from less than a meter to tens of meters. Within the lenses are numerous minor shear zones and fractures with veins of calcite and quartz; portions of these lenses are brecciated or foliated. The thinly-bedded sedimentary rocks are folded and disrupted by cataclasite and tectonic breccia. Limestone is commonly deformed into cataclasite, but plastically-deformed, foliated calc-mylonite also occurs along some of the shear zones in the unit.

Immediately northeast of the Hassanabad Unit, near Neyriz, rocks of the Sanandaj–Sirjan block are regionally metamorphosed (e.g. Adib, 1978). Although mylonites in the shear zones around several thrust sheets and in the marbles in the 'Tang-e Hanna' area attest to local, fault-related amphibolite facies metamorphism (Pamic et al., 1979; Pamic and Adib, 1980, 1982), no evidence of regional metamorphism exists in Neyriz ophiolite complex or in the Hassanabad Unit.

In this paper we focus only on the geochemistry of the volcanic and volcanioclastic rocks of the Hassanabad Unit and are not concerned with the tectonics of emplacement of these rocks or the geochemistry of the structurally underlying ophiolitic sequences.

4.1. Petrography

Thin section examination reveals that brecciation and cataclastic shearing have severely modified the textures of the volcanic and volcanioclastic rocks of the Hassanabad Unit but have modified the mineralogy only to a minor extent. From a textural point of view, the volcanic rocks and volcanic clasts in the volcanioclastic rocks have preserved volcanic textures, although vesicle filling, shear-related foliation and/or calcite microveins are evident. The non-pelagic rocks of the Hassanabad Unit are divided into volcanic and volcanioclastic groups (Tables 1 and 2). The volcanioclastic rock group includes sandstone and sedimentary breccia with clasts of a variety of volcanic and intrusive rocks.

The primary mineralogy of the volcanic rocks is dominated by euhedral-to-subhedral plagioclase feldspar (some normally compositionally zoned) occurring as both phenocrysts and in the groundmass. Clinopyroxene occurs in the groundmass and to a much lesser extent as phenocrysts. The lack of evidence for moderate-to-high temperature hydration, even in the most highly altered samples, argues against water having played a major role in the alteration. The mineralogical alteration is dominated overwhelmingly by carbonate occurring as infilling of vesicles, and to a lesser extent, by microveining and partial replacement of plagioclase phenocrysts and groundmass. The micro-porphyritic volcanic rocks (Table 1) have clusters of plagioclase and pyroxene phenocrysts set within a microlitic groundmass with fine plagioclase needles and pyroxene [Fig. 2(b)]. The non-porphyritic, volcanic rocks have a fine groundmass made of prismatic plagioclase, augite with hourglass structure and diopside [Fig. 2(c)]. The groundmass is altered and has euhedral hornblende, actinolite, epidote, zoisite, chlorite and calcite. Chlorite, epidote and, in places, pumpellylite and prehnite, represent the low grade prehnite–pumpellylite metamorphic facies (Arvin, 1982b), producing the characteristic light green color of these lavas in the field.

The grains in the fine-grained, volcanogenic sandstones are moderately- to well-sorted, angular to subrounded quartz, plagioclase (chloritized in places), pyroxene and lithic fragments, cemented with calcite [Fig. 3(a)]. Clasts in the poorly-sorted, volcanogenic, pebbly sedimentary breccia, are angular to subangular lithic fragments [Fig. 3(b)]. These clasts are mostly porphyritic and non-porphyritic volcanic rocks and intrusive rocks such as diorite, and granite.

4.2. Analytical methods

Whole rock major elements and some trace elements (Nb, Zr, Ti, V, Cr, Fe, Co, Ni) of the volcanic and volcanioclastic rocks in the Hassanabad Unit were determined by a wavelength dispersive, Rigaku 3070 X-ray fluorescence spectrometer utilizing a side-window rhodium target X-ray tube. All analyses were made against standard calibration curves which were prepared using a set of USGS reference standards.

Analysis of the major elements were performed on fused glass disks. The disks were prepared using nine parts lithium borate flux and one part rock powder. The mixture was fused in a crucible of 95% Pt and 5% Au at approx. 1100°C for 10–15 min, to form a homogeneous melt. The melt was then poured into a preheated platinum mold and chilled to a thick glass disk. Analysis of the trace elements were performed on powder pellets, using an equal weight of rock powder and crystalline cellulose binder, pressed at 15
Table 1
Major and trace elements of volcanic and volcaniclastic rocks of the Hassanabad Unit, Neyriz, Iran

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>P₂O₅</th>
<th>LOI</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>61.8</td>
<td>0.48</td>
<td>4.73</td>
<td>5.40</td>
<td>2.27</td>
<td>5.98</td>
<td>4.73</td>
<td>0.70</td>
<td>0.15</td>
<td>5.48</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>55.0</td>
<td>0.51</td>
<td>5.86</td>
<td>6.15</td>
<td>2.88</td>
<td>6.41</td>
<td>6.15</td>
<td>0.17</td>
<td>0.15</td>
<td>6.30</td>
<td>101</td>
</tr>
<tr>
<td>A10</td>
<td>54.5</td>
<td>0.74</td>
<td>5.86</td>
<td>7.91</td>
<td>4.76</td>
<td>6.68</td>
<td>5.41</td>
<td>0.13</td>
<td>0.13</td>
<td>3.23</td>
<td>103</td>
</tr>
<tr>
<td>A102</td>
<td>54.8</td>
<td>0.62</td>
<td>6.00</td>
<td>9.13</td>
<td>3.81</td>
<td>8.28</td>
<td>6.15</td>
<td>0.11</td>
<td>0.11</td>
<td>2.49</td>
<td>102</td>
</tr>
<tr>
<td>A9</td>
<td>56.5</td>
<td>0.59</td>
<td>6.26</td>
<td>7.65</td>
<td>1.61</td>
<td>8.48</td>
<td>6.55</td>
<td>0.05</td>
<td>0.05</td>
<td>4.38</td>
<td>102</td>
</tr>
<tr>
<td>Avg.</td>
<td>58.4</td>
<td>0.62</td>
<td>7.25</td>
<td>4.18</td>
<td>1.31</td>
<td>4.49</td>
<td>6.55</td>
<td>0.07</td>
<td>0.07</td>
<td>4.57</td>
<td>102</td>
</tr>
<tr>
<td>Avg. a</td>
<td>65.5</td>
<td>0.52</td>
<td>4.00</td>
<td>7.8</td>
<td>2.36</td>
<td>6.99</td>
<td>6.55</td>
<td>0.40</td>
<td>0.13</td>
<td>5.00</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 10</td>
<td>63.5</td>
<td>0.32</td>
<td>4.04</td>
<td>7.8</td>
<td>2.62</td>
<td>6.16</td>
<td>6.99</td>
<td>0.13</td>
<td>0.17</td>
<td>5.14</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 12</td>
<td>64.8</td>
<td>0.45</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.83</td>
<td>0.17</td>
<td>0.15</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 14</td>
<td>60.3</td>
<td>0.64</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 14A</td>
<td>49.9</td>
<td>0.88</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 14B</td>
<td>49.9</td>
<td>1.24</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 13</td>
<td>49.9</td>
<td>1.24</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 12B</td>
<td>49.9</td>
<td>1.24</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 10A</td>
<td>49.9</td>
<td>1.24</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 5A</td>
<td>49.9</td>
<td>1.24</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 7</td>
<td>49.9</td>
<td>1.24</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 10</td>
<td>49.9</td>
<td>1.24</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 12</td>
<td>49.9</td>
<td>1.24</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
<tr>
<td>Avg. 14</td>
<td>49.9</td>
<td>1.24</td>
<td>4.00</td>
<td>7.8</td>
<td>2.62</td>
<td>3.15</td>
<td>6.63</td>
<td>0.21</td>
<td>0.18</td>
<td>5.07</td>
<td>102</td>
</tr>
</tbody>
</table>

**Notes:**
- The average for the volcanic rocks does not include sample A9.
- ± Means concentration was below detection.

---

### Table 2
CIPW norms and minerals identified by petrography and/or XRD in the volcanic rocks of the Hassanabad Unit, Neyriz, Iran

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>17.74</td>
<td>Veins of qtz.</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Orthoclase</td>
<td>0.43</td>
<td></td>
<td>1.06 Plag. phenocr. and in the groundmass</td>
<td>0.77</td>
<td></td>
<td>0.83</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>33.46</td>
<td></td>
</tr>
<tr>
<td>Albite</td>
<td>41.73</td>
<td>Plagioclase as phenocrysts and in the groundmass</td>
<td>54.64</td>
<td>49.58 Clots of plag. laths</td>
<td>48.97 Laths and aggregates of plag.</td>
<td>38.82 Zoned and resorbed laths of plagioclase</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anorthite</td>
<td>19.58</td>
<td></td>
<td>20.65</td>
<td>19.07</td>
<td>16.50</td>
<td>7.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nepheline</td>
<td>0.00</td>
<td></td>
<td>0.00 Augite altered to amphibole</td>
<td>0.00 Plagioclase as needles in groundmass</td>
<td>1.16</td>
<td>3.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diopside-wo</td>
<td>4.38</td>
<td></td>
<td>4.93</td>
<td>5.33</td>
<td>9.88</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diopside-en</td>
<td>1.90</td>
<td>Pyroxene</td>
<td>2.26</td>
<td>2.48</td>
<td>4.28 Phenocr. of augite</td>
<td>1.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diopside-fs</td>
<td>2.47</td>
<td></td>
<td>2.63 Euhedral hornblende</td>
<td>2.80</td>
<td>5.60</td>
<td>5.41 Calcite replacing plagioclase</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypersthene-en</td>
<td>4.02</td>
<td>Chlorite</td>
<td>4.50</td>
<td>1.86 Specs of pyroxene in groundmass</td>
<td>0.00 Small pyroxene in groundmass</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypersthene-fs</td>
<td>5.23</td>
<td>Opaques</td>
<td>5.24</td>
<td>5.24 Opaques</td>
<td>2.10</td>
<td>0.00 Calcite vug and veinlets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forsterite</td>
<td>0.00</td>
<td>Epidote</td>
<td>0.57</td>
<td>0.57 Secondary calcite</td>
<td>5.31</td>
<td>3.73</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fayalite</td>
<td>0.00</td>
<td>Secondary calcite</td>
<td>0.73</td>
<td>0.73 Chlorite</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetite</td>
<td>1.23</td>
<td>Chlorite</td>
<td>1.42</td>
<td>1.42 Chlorite</td>
<td>2.18</td>
<td>0.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ilmenite</td>
<td>0.95</td>
<td>XRD shows albite &amp; diopside</td>
<td>1.02 XRD shows albite &amp; augite</td>
<td>1.41 Epidote</td>
<td>1.19 Pyroxene</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apatite</td>
<td>0.34</td>
<td></td>
<td>0.37</td>
<td>0.50</td>
<td>0.46</td>
<td>0.42</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td>100.00</td>
<td></td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>98.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
tons/square inch in a Spec cap for 4–6 min. In general, the lower limit of detection (lld; for XRF analyses) for the detected trace elements (Nb, Zr, Ti, V, Cr, Fe, Co, Ni) is 4 ppm. The lld is based on peak counts exceeding background counts outside an error range of ±7 S.D. for averaged background counts, for standards containing 4 greater ppm of the element. However, Y, Nb and Zr were also analyzed using the higher precision inductively coupled plasma mass spectrometer (ICPMS; see below).

The rare earth elements (REE) and other trace elements such as Rb, Sr, Ba, Hf, Ta, Pb, Th, U, Y, Nb and Zr were determined by an ICPMS using a standard Teflon vial acid-digestion procedure involving a mixture of HF-HClO₄-HNO₃. All samples were spiked to 50 ng/ml using indium.
as an internal standard. REE analyses for this study were calibrated against a set of working multi-element solutions. The working standards were produced by mixing single element SPEX standard solutions (SPEX Industries, USA). All the solutions were introduced via a peristaltic pump and analyses were performed using a SOLA ICPMS at Georgia State University. The average precision for the major and trace elements during this study is given in Table 1 under the BHVO-1 column. At the 0.5±2 ppm abundance level in the rocks, the relative precision for most elements by ICPMS is 4.5 % or better (range is 1.0±6.0%). An indication of accuracy is given by measured and recommended values for BHVO-1 standard (see columns measurements and recommendations in Table 1). The recommended values for major oxides are from Gladney and Roelandts (1988) while values for trace elements are principally from Govindaraju (1989). Minerals were identified by a petrographic microscope and a Phillips Model 12045 X-ray diffractometer.

4.3. Major elements

Analyzed samples were selected in the field to avoid as much as possible those that appear highly deformed or altered. Major-element analyses of the volcanic rocks clearly reveal the extent of secondary geochemical alteration that occurred during the cataclastic deformation in some samples. In the volcanic samples that have had only minor carbonate alteration, the major element chemistry is recognizably basaltic/andesitic in character, albeit altered to a minor degree.

Table 1 gives the major and trace element distribution of the representative, less-altered volcanic–volcaniclastic rocks of the Hassanabad Unit and depicts the symbols used in the geochemical diagrams in the trace element analysis. The LOI values reflect secondary alteration of the rocks which is indicated by the presence of veining and vug-filling by calcite. The Hassanabad Unit’s volcanic rocks plot in the island arc calc-alkaline field of the TiO₂–MnO–P₂O₅ diagram [Mullen, 1983; Fig. 4(a)]. Except for the more alkaline sample A9, the volcanic rocks show subalkaline compositions on the alcalis vs. SiO₂ plot [Fig. 4(b)].

4.4. Trace element distributions

Plots of Zr against selected HFS elements such as Ti, Ce, Hf (Pearce and Cann, 1973; Pearce, 1975; Gamble et al., 1993) can potentially discriminate between eruptive environments such as low-K tholeiite (LKT), calc-alkaline basalt (CAB) and ocean floor basalt (OFB). In a Zr–Ti diagram, the volcanic rocks of the Hassanabad Unit plot in the CAB field [Fig. 5(a)]. The volcanogenic sandstones have higher Zr values than volcanic rocks and the breccia.

The ternary diagrams Nb–Zr–Y (Meschede, 1986), Ti–Zr–Y and Ti–Zr–Sr are commonly applied to distinguish OFB, LKT and CAB (Pearce and Cann, 1973; Meschede, 1986). The Nb*2–Zr/4–Y plot [Fig. 5(b)] shows that, except for the Zr-rich sandstones, the volcanic–volcaniclastic rocks of the Hassanabad Unit can be attributed to the VAB composition (fields C and D). Although the concentration of Nb in sample A9 was below the detection limits (Table 1), its Y and Zr values are comparable to the other volcanic rocks [Fig. 5(c)]. Almost all volcanic–volcaniclastic rocks plot in the CAB field (fields B and C) of the ternary plot of Ti/100–Zr–Y*3 [sandstones have higher Zr values; Fig. 5(c)]. The ternary diagram, Ti/100–Zr–Sr/2, corroborates the CAB compositions for the volcanic–volcaniclastic rocks [Fig. 5(d)]. The Th–Hf–Nb plot (Fig. 6) relates all the volcanic–volcaniclastic rocks in the Hassanabad Unit to a destructive plate margin and its field of differentiates.
Normalized multi-element plots, with elements arranged according to increasing incompatibility, have been used to analyze the source of the magma and the origin of arc extrusive rocks in supra-subduction zone ophiolites (Pearce, 1982, 1996). Assuming that elements such as Nb, Zr, Ti, Y, Hf, Yb and HREE are dominantly mantle wedge-derived (i.e., not contributed by the slab), the relative contributions of the mantle and subducting slab in subduction zone basalts can be estimated from the N-MORB-normalized distribution of a series of incompatible elements (Pearce, 1982, 1983; Pearce and Parkinson, 1993).

The N-MORB-normalized multi-element distribution patterns of the volcanic–volcaniclastic rocks of the Hassanabad Unit (Fig. 7) indicate depletion of most of the HFS elements with respect to N-MORB, and depletion of Nb relative to Th and Ce. However, as is typical of the CA-VAB, the absolute concentration of Nb is a little higher than that in the N-MORB. The concentrations of the LIL elements in these volcanic rocks are all greater than those in the N-MORB (Fig. 7).

The CA-VAB-normalized multi-element patterns of the mean volcanic and volcaniclastic rocks [Fig. 8(a)] show that most of the trace element concentrations (except for the LIL) reasonably fit the CA-VAB pattern. The primitive mantle-normalized patterns of these rocks [Fig. 8(b)] show the relative enrichment of the LIL relative to the HFS elements by a gradual decrease of the concentrations to the right, and the more-or-less uniform behavior of the Eu, Gd, Dy, Y, Er, Yb and Lu.

The fertile MORB mantle (FMM)-normalized patterns of elements, with varying degrees of incompatibility, in arc lavas, give a measure of the relative importance of degree
of partial melting and source depletion/enrichment events in the mantle (Pearce and Parkinson, 1993). Such patterns show that arcs that do not have proximal backarc basins exhibit N-MORB-like enriched sources. The FMM represents the upper mantle reservoir from which the N-MORB is derived (Pearce and Parkinson, 1993). Under low to moderate degrees of partial melting, an undepleted MORB mantle source produces enrichment in the order VHI > HI > MI, where VHI are very highly incompatible elements, and HI and MI are the highly incompatible and moderately incompatible elements, respectively. The patterns becomes flat at high degrees of melting (Pearce and Parkinson, 1993; Pearce and Peate, 1995). The FMM-normalized patterns of the volcanic and volcaniclastic rocks of the Hassanabad Unit [Fig. 8(c)] exhibit the typical VHI > HI > MI trend representative of the low to moderate degrees of partial melting of an undepleted mantle source.

The ratios of some elements in ophiolitic lavas can be used as discriminants to characterize the composition of the parental magma and magma source and account for the effects of fractionation that occur during partial melting or fractional crystallization (Saunders et al., 1980; Pearce, 1996). The ratios of immobile elements (e.g. HFS, REE) in basaltic systems whose relative abundances remain essentially constant (e.g. during hydrothermal alteration or metamorphism of basalt) to the elements with low bulk distribution coefficients (e.g. Ti, Zr, P, Nb, Y, La, Ba, REE), are particularly useful as discriminants in determining the tectonic setting of magma eruption (Cann, 1970; Pearce and Cann, 1973; Pearce, 1975; Saunders et al., 1980). A series of selected elemental ratios of the volcanic rocks of the Hassanabad Unit show a good correlation with the ratios of the CA-VAB (Fig. 9), further suggesting their calc-alka-

5. Summary and conclusions

Regional metamorphism of rocks, at all facies below partial melting, generally does not alter the major-element chemistry of the original rocks except for SiO₂, CO₂, H₂O, and carbonates (Beach, 1974; Hyndman, 1985, p. 467). Even in massive shear zones where original igneous rocks have been converted to extremely fine-grained mylonites, chemical changes can be generally minor (e.g. La Tour, 1979). To alter appreciably the bulk chemistry of rocks undergoing deformation, ongoing production or introduction of fluid must overwhelm the deformation process itself. This is a so-called fluid-dominated regime. Otherwise, the regime is rock-dominated in which the rock buffers the fluid composition, keeping the rock from changing its composition appreciably (Fyfe et al., 1978).
The rare earth elements (except La), and other trace elements such as Y, Ti, Zr, Hf, Nb, Cr and Th are believed to be the least sensitive to secondary processes that occur within subduction zones (Muecke et al., 1979; Saunders et al., 1980; Campbell et al., 1984; MacLean and Kranidiotis, 1987; Pearce, 1996; Kerrich and Wyman, 1996). Of these, Th, Nb, Zr and Ti are believed to be less mobile than the LREE and behave like the HREE during seafloor hydrothermal alteration under low to moderate water/rock ratios and low grade metamorphism (Pearce, 1983; Humphris, 1984; Kerrich and Wyman, 1996). Of these, Th, Nb, Zr and Ti are believed to be less mobile than the LREE and behave like the HREE during seafloor hydrothermal alteration under low to moderate water/rock ratios and low grade metamorphism (Pearce, 1983; Humphris, 1984; Kerrich and Wyman, 1996).

Despite the zeolite and greenschist facies metamorphic alterations, the major and trace element geochemistry of the volcanic–volcaniclastic rocks of the Hassanabad Unit give consistent geochemical evidence for subduction-related magmatism and sedimentation, suggesting that major redistributions of trace elements have not occurred. The subduction-related section of the Hassanabad Unit includes calc-alkaline volcanic and volcanogenic sandstone and breccia with clasts of arc volcanic rocks and diorite. The trace element distributions of the volcaniclastic rocks are similar to those of the volcanic rocks indicating: (1) that the igneous clasts in the volcaniclastic rocks have the same chemical composition as the associated volcanic rocks; (2) that sedimentation and subsequent alterations during diagenesis and low temperature metamorphism did not redistribute the
trace elements in the clasts or matrix of the volcanogenic sandstone and breccia.

The presence of arc-related volcanogenic sandstone and sedimentary breccia, intercalated with pelagic sediments and arc volcanic rocks in the Hassanabad Unit, indicates that the arc volcanic rocks were erupting into a deep basin where radiolarian chert was being deposited and into which coarse-grained volcaniclastic debris was probably transported by turbidity currents from nearby arc volcanoes.

Because volcaniclastic sediments are absent in the adjacent, structurally underlying crustal and mantle sequences (the ophiolite component) of the Neyriz ophiolite complex, we infer the presence of a source of the volcanic debris (i.e. a volcanic arc) to the northeast of the Neo-Tethys trough and its Late Cretaceous subducting crust, implying a northeast-dipping subduction zone. The subduction polarity and the presence of the volcanic arc have important implications for the tectonic interactions in this part of the Neo-Tethys basin during the Late Cretaceous, and for the emplacement of the Neyriz ophiolite complex. Although this is the subject of another paper, we speculate that the arc-related andesitic-basaltic rocks were erupting in the northeastern margin of a narrowing ocean basin where turbidity currents transported the volcaniclastic debris from an adjacent arc which lied to the northeast, and deposited them intercalated with radiolarian chert and pelagic sediment.

The tectonic intercalation of the Hassanabad Unit with the Cretaceous limestone and their thrust contact with the crustal and mantle sequences of the Neyriz ophiolite complex along northeast-dipping thrust faults, suggest that the basin in which the Hassanabad rocks were deposited lied above (i.e. in a forearc basin) a northeast-dipping subduction zone. The underlying ophiolite component probably represents offscraped or underplated slivers of the Neo-Tethyan subducting oceanic lithosphere. The tectonic juxta-

Fig. 9. Distributions of the elemental ratios (Ce/Yb means the Ce/Yb ratio) of the mean subalkaline and alkaline (A9) volcanic rocks and volcanogenic sandstone and breccia normalized to the ratios of the CA-VAB. Normalizing values are from Sun and McDonough (1989). See Table 1 for symbols.

Fig. 10. Mean rare earth element (REE) distributions in the volcanic–volcaniclastic rocks of the Hassanabad Unit: (a) normalized to the N-MORB (+); (b) normalized to the chondrite. Normalizing values are from Sun and McDonough (1989). See Table 1 for the symbols.

Further narrowing of the Neo-Tethyan oceanic basin emplaced the disrupted slivers of the oceanic crust, possibly with their overlying arc volcanic–volcaniclastic unit, onto abyssal and continental slope, and later, the shelf facies of the passive continental margin of the Afro–Arabian plate. The final contraction of the area during the Miocene led to the thrusting of parts of the arc and emplacement of the Hassanabad Unit and its carbonate platform above the ophiolite complex. The Crush Zone, which includes cataclastically-deformed rocks of both the southwestern edge
of the Sanandaj–Sirjan block and the northeastern part of the ophiolite complex, formed as a result of the Miocene contractual tectonics. The Miocene contractual deformation led to renewed thrusting and slicing in the ophiolite complex and the cataclastic intercalation of the volcanoclastic—volcanic rocks with the Cretaceous limestone at the southeastern edge of the Sanandaj–Sirjan block.

Acknowledgements

We are grateful for funds provided to Hassan Babaie by Georgia State University and to Abed Babaei by Cleveland State University and the United Nations’ T.O.K.T.E.N program for their field work. Acknowledgement is made to Mohammad Reza Sayyad and A. Afrasiabian, both at the Ministry of Energy, Water Resources Research Organization, Shiraz, Iran, for providing logistical support for Hassan Babaie’s field work. Abed Babaie thanks Mohsen Arvin and M. Hashemi-Tangestani for logistical support in the field. The ICPMS facility at GSU was partially funded by the NSF grant EAR 94-05716 awarded to A.M. Ghazi and D.A. Vanko. We thank Drs. Simon Haynes and U. Knittel for their valuable, critical and constructive comments and reviews that led to significant improvement of this manuscript.

References


