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The evolution of arc magmatism related to Palaeotethys in the west of Salmas, north of the Sanandaj-Sirjan Zone, Iran

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The Mingol-Mamakan gabbroic-appinitic intrusions are located in the northwestern part of Iran and belong to the Sanandaj-Sirjan Zone (SSZ). These intrusions have had a significant impact on the evolution of the northwestern part of the SSZ during the Late Carboniferous. The rocks typically include layered and massive gabbros-gabbrodiorites. The age of the layered gabbros is between 322 and 314 Ma and they mainly consist of leuco-gabbro, meso-gabbro, melano-gabbro, anorthosite, and hornblendite (appinite) with either gradational or sharp contacts. The massive gabbros (300.7 ±1.5 Ma) are mostly composed of leuco-gabbro, meso-gabbro, melano-gabbro, and hornblendite. Most of these rocks are appinitic in composition. The intrusions show no obvious deformation. Therefore, mineral composition changes in the rocks were controlled by crystallisation processes, such as fractionation in the magma chamber. Different rock types of the tholeiitic magma series were probably derived from partial melting of a spinel lherzolite upper mantle co-genetic source. Geochemical information and dating from the Mingol-Mamakan intrusive rocks reveal that the intrusions were formed of subduction-related immature or sub-mature island arc tholeiitic basalt which was enriched in Al_2O_3, FeO, Sr and depleted in K and Nb. Subsequently, primary tholeiitic arc basalt magma underwent fractional crystallisation to form intrusive rocks in the lower crust. Geochemical modelling based on the partition coefficient of elements in minerals indicated that trace element concentrations (large-ion lithophile elements, LILEs, high field strength elements, HFSE, and rare earth elements, REEs) in the Mingol-Mamakan intrusions throughout crystallisation were controlled by variable amounts of common minerals such as amphibole, clinopyroxene (for all trace elements), plagioclase (only for LILE) and probably spinel in the source rock (only for HFSE). Moreover, elements of the first transition series of the periodic table were mainly controlled by orthopyroxene, olivine and possibly by clinopyroxene and amphibole in much smaller amounts.

Key words: layered gabbros, massive gabbrodiorite, appinite, geochemical-mineralogical modelling, tectono-magmatic model, Zagros.

INTRODUCTION

Petrological and geochemical studies on basalts, gabbros and related rocks have indicated that many of these rocks do not represent primary mantle-derived magma in equilibrium with mantle assemblages (Raymond, 2007); these rocks have undergone some degree of differentiation in crustal magma reservoirs. Typically, ophiolite complexes include layered gabbroic and ultramafic rocks representing accumulation which formed in axial magma chambers beneath the oceanic spreading centres, or in back-arc basins above subduction zones. In addition, gabbro samples have also been found in oceanic fractured zones and oceanic extensional core complexes (Ildefonse et al., 2007; Lesnov et al., 2015). Gabbros are rarely seen *in situ* on oceanic islands and mainly occur at depth within oceanic islands (Gill, 2010). These intrusions are also widespread in large igneous provinces, such as the Muskox layered intrusion (Raymond, 2007; Gill, 2010) and continental flood basalt provinces such as Bushveld (Best, 2003).

Continental alkaline volcanic provinces associated with intra-continental rifting (e.g., Gardar in Greenland), consist of gabbros as doleritic and composite dyke swarms together with nepheline syenite and alkali granite (Best, 2003; Gill, 2010). In addition to these cases, some gabbroic rocks have been reported from many tholeiitic and calc-alkaline volcanic rocks in island arc settings, such as the Lesser Antilles (Arculus and Wills, 1980), the Aleutians (Conrad and Kay, 1984; Bacon et al., 2007) and Arenal volcano in Costa Rica (Beard and Borgia, 1989). These are typically layered gabbro plutons that occur beneath the island arc volcanoes.

Since subduction-related magmas tend to be richer in dissolved H_2O than other mantle-derived magmas, many such gabbroic rocks are hornblende gabbro (or mafic appinite; Wright and Bowes, 1979; Fortey et al., 1994; Murphy, 2013). Hornblende is not a cumulus phase but typically forms poikilitic oikocrysts enclosing olivine, clinopyroxene and orthopyroxene (e.g., Claeson and Meurer, 2004) and may be the product of reaction between these minerals and coexisting melt (Murphy, 2013). Specifically, hornblende is markedly more abundant in plutonic gabbros relative to basic volcanic rocks within the

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same island arcs. Hornblende phenocrysts are seen only in andesite lavas with SiO_2 >54% in the island arcs. Gabbros are also found in continental-collision zones, for instance the Fongen-Hyllingen complex in the Caledonian mountains of Norway (Gill, 2010).

The purpose of this paper is estimation of the geochemical characteristics and determination of trace-element distributions between the layered and massive gabbrodiorite--appinite-forming minerals of Mingol-Mamakan recording evolution of arc magmatism related to Palaeotethys in the west of Salmas, north of the Sanandaj-Sirjan Zone (NW Urumieh, SSZ; Fig. 1), Iran.

GEOLOGICAL SETTING

The Zagros collision zone is located in the tectonic crossroads of the Alpine-Himalayan belts. Its formation results from large-scale convergence between Eurasia and Gondwana-derived fragments, as exemplified by accreted ophiolitic belts. As for other segments of the Alpine-Himalayan belts, the Zagros collision zone formed as a result of disappearance of the Neo-Tethyan Ocean (e.g., Berberian and King, 1981; Dercourt et al., 1986; Alavi, 1994; Stampfli and Borel, 2002; Mohajjel et al., 2003; Agard et al., 2005, 2011; Monsef et al., 2010; Mouthereau et al., 2012; Mohajjel and Fergusson, 2014) between Arabian plate and Eurasia. There is a growing body of evidence in support of Late Eocene to Oligocene initial collision (e.g., Agard et al., 2005, 2011; Ballato et al., 2011; Mouthereau et al., 2012; Mohajjel and Fergusson, 2014). The position of the suture zone between Arabia and Eurasia, regarded by most authors as lying along the Zagros Thrust-fold Belt (Fig. 1; Stöcklin, 1968; Agard et al., 2005; Paul et al., 2010), is also discussed (Alavi, 1994). Three major tectonic elements – the Zagros Thrust-Fold Belt, the Sanandaj-Sirjan Zone (SSZ), and the Urumieh-Dokhtar magmatic zone (UDMZ; Alavi, 1994) or belt (Fig. 1) – are recognized in the NW, western, and SW parts of Iran as they are related to the subduction of Neo-Tethyan oceanic crust and subsequent collision of the Arabian plate with the central part of the Iran micro-continent.

The SSZ is a narrow zone of highly deformed rocks located between the towns of Sirjan and Esfandagheh in the south-east and Urumieh and Sanandaj in the north-west (Mohajjel et al.,

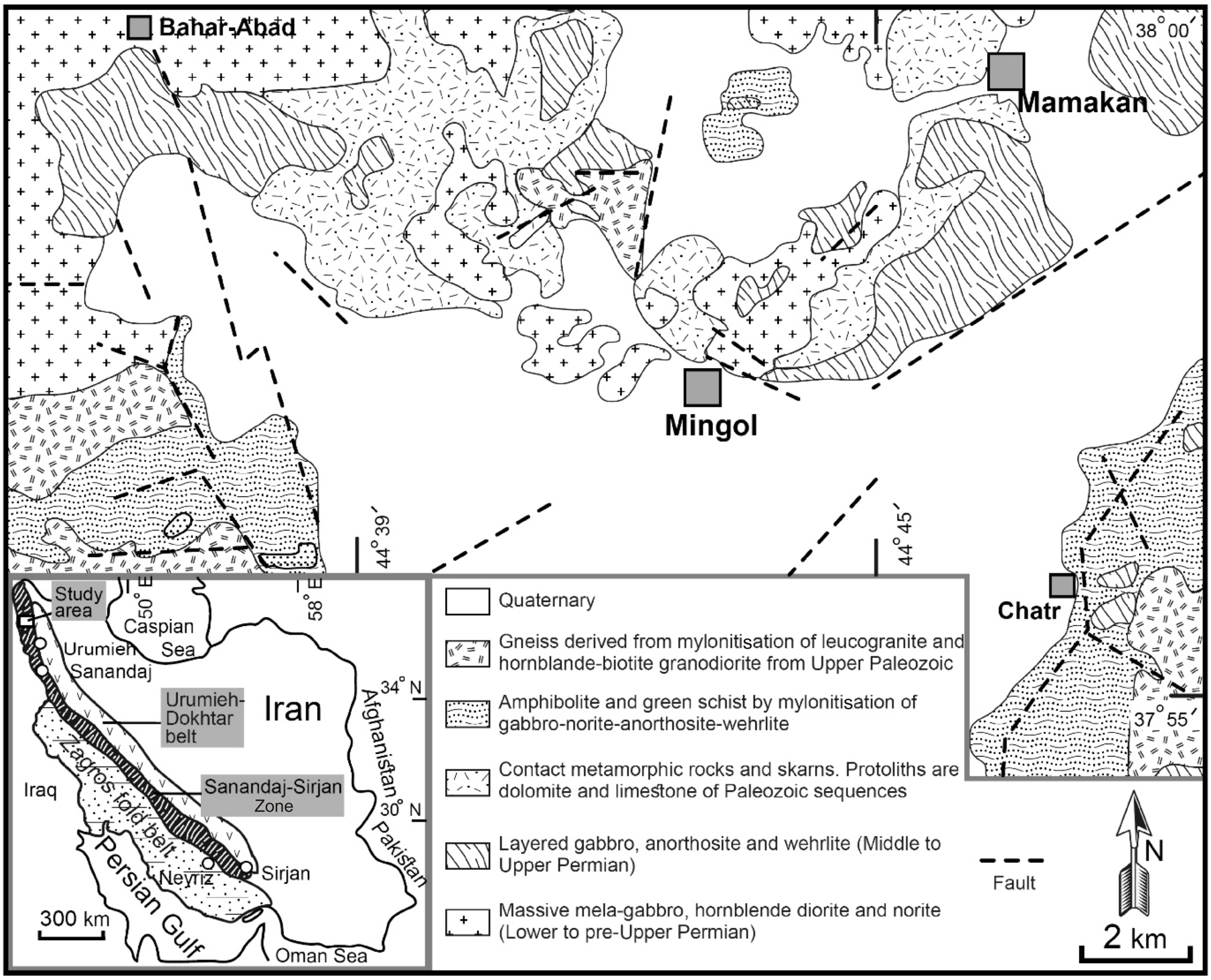

Fig. 1. Simplified geological map of northwestern Oroumieh (modified after Ghaemi, 2004); the bottom left of the figure is a simplified map of Iran and locations of the UDMZ (Urumieh-Dokhtar magmatic zone or belt) and SSZ (modified after Stöcklin, 1968)

2003). The rocks in this zone are the most highly deformed in the Zagros Belt, and share the NW–SE trend of surrounding structures. This zone is dominated by Mesozoic rocks; Paleozoic rocks are generally rare, but they are common in the southeast (Berberian, 1995). The SSZ is characterized by metamorphosed and thoroughly deformed rocks associated with abundant deformed and undeformed plutons, as well as widespread Mesozoic volcanic rocks.

The Paleogene-Neogene Urumieh-Dokhtar magmatic zone (UDMZ) or belt trends NW–SE parallel to the Zagros Thrust-Fold Belt between the SSZ and the Central Iran Zone. This narrow zone of arc volcano-plutonic rocks is located on the western border of Central Iran Zone (e.g., Berberian and King, 1981; Mohajjel et al., 2003; Sepahi et al., 2013). Magmatism in the UDMZ occurred mainly during the Eocene but later resumed, after a dormant interval, during the Late Miocene to Plio-Quaternary (e.g., Berberian and King, 1981; Mouthereau et al., 2012; Mohajjel and Fergusson, 2014).

The Mingol-Mamakan gabbroic intrusions (Fig. 1), located in the north-west of Urumieh, are part of the northern SSZ (Stöcklin, 1968). Based on the studies of Alavi-Naini (1972), the area is located between the Central Iran Zone in the east and the SSZ in the west. According to Nabavi (1976), the area is located in the Khoy-Mahabad Zone (northern part of the SSZ). Lithologically, the area shows specific characteristics, such as rock types and structures of three zones: Central Iran, Sanandaj-Sirjan, and Alborz in the Western Azerbaijan province (Ghaemi, 2004). Previous authors working on this area have based their ideas on the research of Haghipour and Aghanabati (1976). Based on these investigations, most of metamorphic rocks in this area were formed in the Precambrian. On the other hand, the formation of these rocks has been related to Paleozoic events by Ghaemi (2004). He believed that the granitic-gabbroic intrusions were injected into the metamorphic rocks in the Late Paleozoic. Hence, the study area would be probably the edge of the Paleozoic platform of Central Iran. This part of Central Iran is known as the UDMZ. The main characteristics of the SSZ cannot be seen in the study area, though this area is the northwestern boundary of the Sanandaj-Sirjan shear zone (Ghaemi, 2004).

The Paleozoic platform of Central Iran was affected by tensional forces resulting from ascending mantle diapirs in the Late Paleozoic (Ghaemi, 2004). As a result of this process, continental rifting was developed in this area and crustal thinning occurred while basaltic magmas were formed from partial melting of the upper mantle. Additionally, there are peraluminous granites synchronous with mafic magmatism in this area. These are in contact or intercalated with gabbroic rocks (Ghaemi, 2004; Asadpour, 2012; Fazlnia and Alizade, 2013; also see below).

Based on field observations (Ghaemi, 2004), the Mingol-Mamakan gabbros can be subdivided into: (a) layered gabbro-ultramafic, including ultramafic, rocks, and (b) massive gabbrodiorite (Fig. 2A, B). The Mingol-Mamakan layered gabbros (Fig. 2C, D) along with massive gabbrodiorites and minor ultramafic rocks are all products of mafic magma injection (co-magmatic process) and evolved in a Paleozoic magma chamber (Ghaemi, 2004). Mafic and ultramafic rocks of the Mingol-Mamakan intrusions are composed of gabbro, anorthosite, wehrlite, hornblendite, and hornblende diorite (Figs. 1 and 2). Amphibole in the hornblendite is edenitic in composition (Ghaemi, 2004). According to Ghaemi (2004), wehrlite, dunite and harzburgite were altered to hornblende- or serpentine-rich rocks during metasomatism. Some exposures show granitic dykes which were intruded into the gabbros and led to the formation of a metasomatic rim at the contact (Fig. 2F). These granitic dykes are younger than the Ghoshchi A-type granites (Ghaemi, 2004).

Intrusion of gabbroic magmas into mature crust increased heat flow and caused partial melting at the base of the crust and the generation of granitic magmas. Thus bimodal magmatism was synchronous with crustal extension (Ghaemi, 2004; Shafaii Moghadam et al., 2015).

Magma mixing and magma mingling have occurred between the gabbrodioritic (massive gabbrodiorites) and A-type granitic liquids in the study area (Fig. 2A). Asadpour (2013a, b) determined U-Pb zircon Laser-Ablation ages of the massive gabbrodiorites which are mostly appinite, as ca. 300.7 ±1.5 Ma and leuco-granites as ca. 300.3 ±1.5 Ma. In contrast, Shafaii Moghadam et al. (2015) recognized that A-type granites and gabbronorites near the study area comprise a bimodal magmatic suite that intruded Ediacaran-Cambrian gneiss and are good representatives of Carboniferous igneous activity. They indicated that gabbronorites (gabbros-gabbrodiorites) and A-type granites were emplaced simultaneously at ~322–314 Ma, based on precise SIMS U-Pb zircon ages. Based on this evidence, all rock types (gabbros and granitoids) were formed in the Late Carboniferous. Therefore, it is likely that these intrusions have the same source and gabbros and granites display bimodal distribution of magma types (Ghaemi, 2004; Shafaii Moghadam et al., 2015; also see Fig. 2A). On the other hand, based on Ghaemi (2004), Asadpour (2012), and Shafaii Moghadam et al. (2015) the influence of mafic magma on the continental crust in Central Iran caused the base of the crust to undergo partial melting to create granitic magma. Based on Shafaii Moghadam et al. (2015), A-type granites and gabbronorites have similar $\varepsilon_{Nd}(t)$ (+1.3 to +3.4 and –0.1 to +4.4, respectively) and zircon $\varepsilon_{Nf}(t)$ (+1.7 to +6.2 and +0.94 to +6.5, respectively). The similar variation in bulk rock $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Nf}(t)$ values and radiometric ages for the granites and gabbronorites indicate a genetic relationship between mafic and felsic magmas, either *via* a crystal fractionation or silicate liquid immiscibility process. On the other hand, based on Fazlnia and Alizade (2013), the parental magma of the rocks under study resulted from partial melting of a metasomatised spinel peridotite wedge as a result of the beginning of Palaeotethys subduction beneath the Mamakan Island arc.

FIELD AND PETROGRAPHIC OBSERVATIONS

The Mingol-Mamakan complex composed of various rock types, field observation indicating that the main rocks have gabbroic and appinitic compositions. These intrusions are typically divided into massive and layered intrusions based on their texture and field characteristics. These two sets are older and younger respectively in comparison with each other (see geological setting section). The layered gabbros-ultramafic rocks showing alternations of of dark minerals are composed of leuco-gabbro, meso-gabbro and mela-gabbro along with appinite (Fig. 2A). In most outcrops, the boundaries between these rocks are gradational and the composition of the different rock types changes from mela-gabbro (appinitic gabbro) to leuco-gabbro (Fig. 2B).

In some areas, the gabbros have gradual boundaries with anorthosite (Fig. 2C), where dark coloured gabbros gradually change to light coloured anorthosite. Large patches of hornblendite (appinite) display sharp contacts with other types of layered gabbros (Fig. 2C–E), whereas gradual boundaries were not observed in related exposures. However, the curved boundaries of the appinites and gabbros without any deformation indicate that both host magma (gabbro) and appinite were semi-crystalline like plastic state during the injection time (Fig. 2C, D). There are small outcrops of clinopyroxenites near the

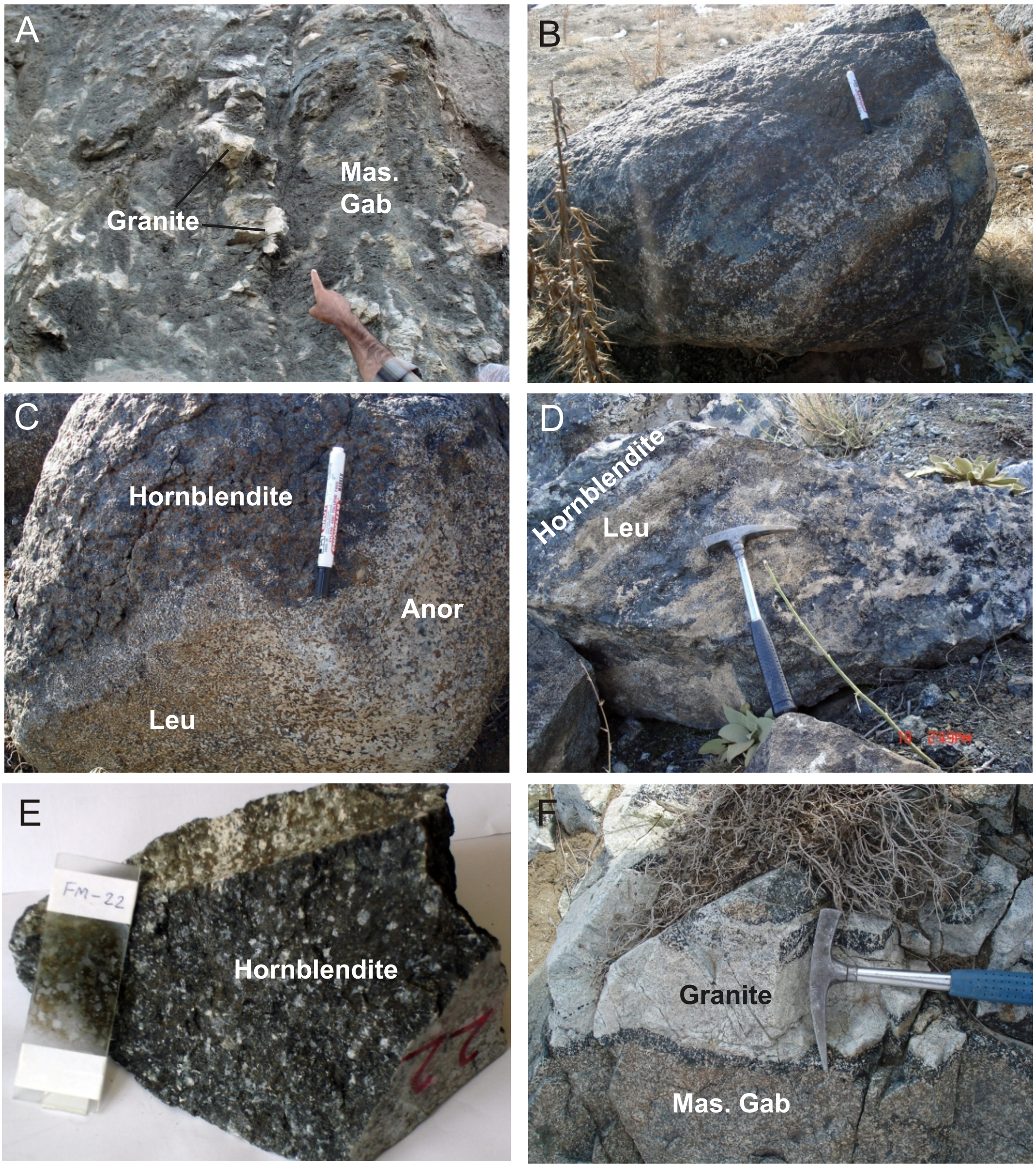

Fig. 2. Photographs of some rock types of Mingol-Mamakan

A – exposure showing magma mixing between massive gabbrodiorites (appinite) and leuco-granite; **B** – layered gabbro; **C** – exposure of hornblendite (appinite) within the layered gabbros with a sharp boundary; **D** – exposures of hornblendite (appinite) and leuco-gabbro in the layered gabbros; **E** – a hornblendite (appinite) with more than 90% hornblende; **F** – occurrence of biotite-amphibole-bearing metasomatic rims around granitic lenses within massive gabbrodiorites; Anor = anorthosite, Gab = gabbro, Leu = leuco-gabbro, Mas. = massive gabbrodiorite

hornblendite. The appinites have different amounts of plagioclase (Fig. 2C, E). Magma mingling of melts with the same ages might have caused such disequilibrium and curved boundaries between the appinites and gabbros. Appinites have been dispersed as enclaves inside the gabbros. Coarse-grained pegmatite veins enriched in plagioclase and hornblende are associated with the appinites which locally show gradual contacts.

The massive gabbrodiorites are seen in mixed structures (Fig. 2A) or have sharp contacts with the leuco-granites. Occurrence of loops containing amphibole-biotite around the mixed granite lenses with massive gabbrodiorites imply metasomatic exchanges between the granite and mafic magmas. Hence, both gabbros and granitoids have the same ages (Fig. 2A). Massive gabbrodiorites show a granular texture and are mostly composed of plagioclase (20–25 vol.%), clinopyroxene (10–15 vol.%) and hornblende (50–70 vol.%) with olivine, titanite and opaque (2–5 vol.%) as accessory minerals. Therefore, these gabbros are appinitic in composition (Fig. 3A, B). More clinopyroxenes in massive gabbrodiorites underwent low temperature re-equilibration or metasomatic processes to be changed into amphibole (Fig. 3B).

The massive gabbrodiorites (or appinites) are most probably located in the upper part of the rock outcrops in the study area. Appinites are commonly seen as dykes around host intrusions. In contrast, the layered gabbros and associated hornblendites (appinites) which are cumulates, have formed in the lower and middle parts of the rock outcrops in the study area.

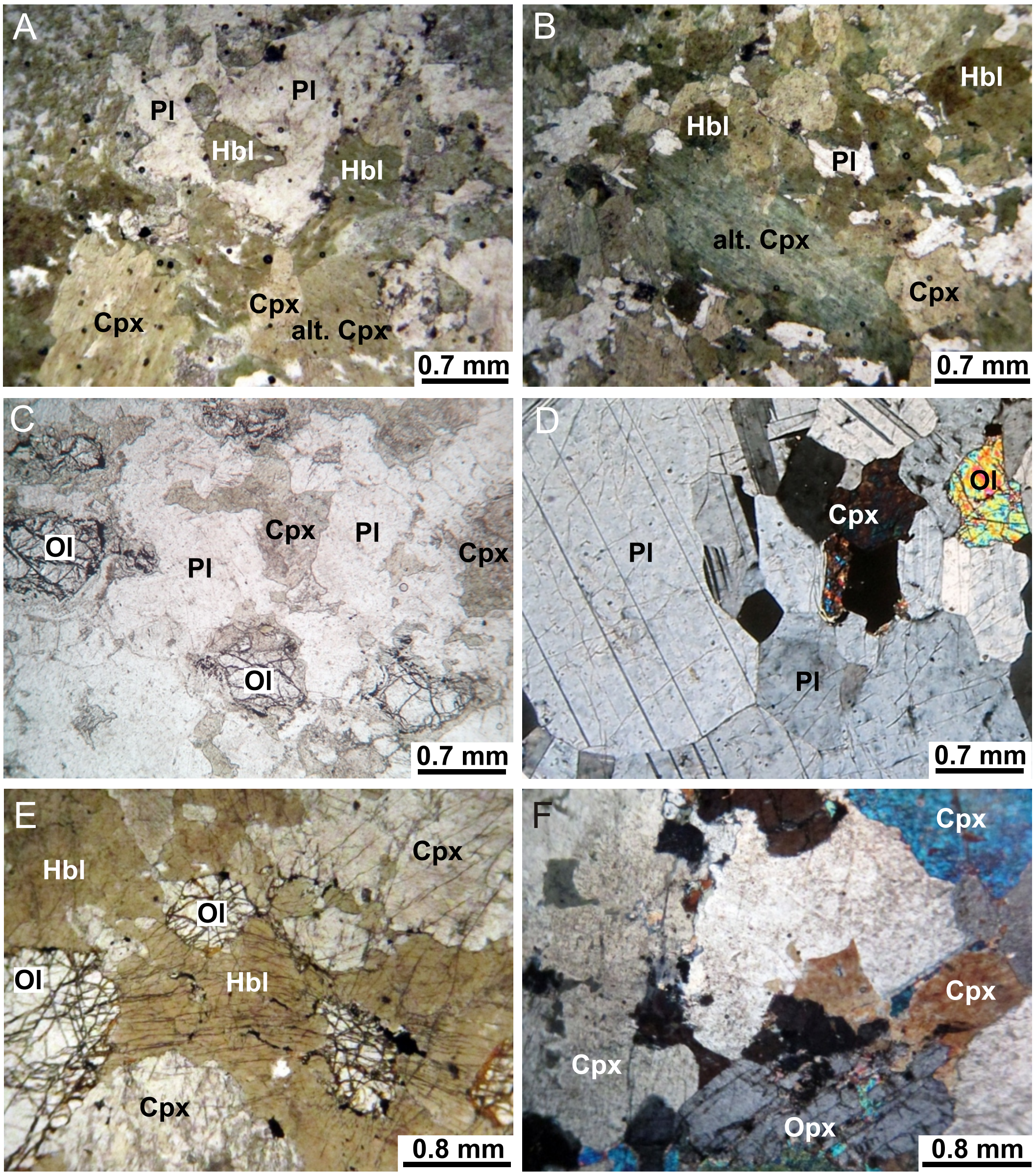

Fig. 3. Selected microscopic photographs from Mingol-Mamakan gabbroic-appinitic intrusions (PPL light)

A – a massive meso-gabbrodiorite (PPL light); **B** – a massive mela-gabbrodiorite (PPL light); some clinopyroxene are crystals altered to amphibole (alt. Cpx) (PPL light); **C** – mineral assemblages in the layered gabbros (PPL light); **D** – an anorthosite in the layered gabbros (XPL light); **E** – poikilitic texture in hornblendite (appinite) intercalated in the layered gabbros (PPL light); **F** – ferromagnesian minerals assemblages from different outcrops in the layered gabbros (XPL light); abbreviations from Kretz (1983)

According to Ghaemi (2004), the layered gabbros along with the massive gabbrodiorites all are products of a single mafic magma injection event which may have evolved in a Paleozoic magmatic reservoir. However, based on our study, transitions from layered to massive gabbrodiorites were not found in the field. The boundaries are sharp, as parallel planes, without mingling between them. In addition, magma mingling between layered gabbros and granitoids was not observed. Meanwhile, given the geochemical features, the concentrations and behaviour of trace elements (see geochemistry section) indicate that these two types of gabbros have no relationship with each other. Also, based on Asadpour et al. (2013a, b) and Shafaii Moghadam et al. (2015), massive and layered gabbros exhibit different ages of crystallisation.

Mineral assemblages in the layered gabbros mainly consist of plagioclase (15–60 vol.%), clinopyroxene (15–50 vol.%), and olivine (5–35 vol.%). Therefore, these rocks are olivine gabbro in composition (Fig. 3C). Hornblende (2–20 vol.%) and minor amounts of biotite, ilmenite and apatite (<2 vol.%) are present in some of the layered gabbros and some other rock types such as hornblendite. These rocks are coarse-grained and typically show granular texture (Fig. 3C). In some places, coarse-grained hornblende is seen with poikilitic texture. In parts with gradational contact of different layered gabbros, the modal percent of plagioclase, olivine and pyroxene is changed.

Anorthosite parts of layered gabbros have >90% plagioclase (Fig. 3D). In these rocks small amounts of hornblende, clinopyroxene and olivine are present.

Hornblendite (appinite) parts of the layered gabbros have >85 vol.% coarse-grained amphibole. Very large crystals of hornblende surround clinopyroxene and olivine crystals as poikilitic texture (similar to Fig. 3E). Clinopyroxene and olivine occur as subhedral crystals and may have formed as cumulate minerals (Fig. 3E). Plagioclase in these rocks is almost absent. Clinopyroxenite parts of the layered gabbros have >90% clinopyroxene (Fig. 3F). In these rocks small amounts of hornblende, orthopyroxene and olivine are present.

ANALYTICAL METHODS

Samples from the Paleozoic outcrops of the Mingol--Mamakan gabbroic-appinitic rocks were collected across the area selected, after examining satellite images, at non-altered outcrops. Fifteen representative samples were selected for whole-rock chemical analysis. H_2O^- of samples was determined by heating powders at 110°C for 2 h. LOI (loss on ignition) of samples was determined by heating powders of the samples at 1000°C for 2 h. The decreased weights of the powders were then calculated. Major and trace-element abundances (Appendixes 1 and 2*) were determined at the Acme Laboratories in Vancouver, Canada. Total abundances of the oxides are reported on a 0.2 g sample analysed by inductively coupled plasma optical emission spectrometry (ICP-OES) following a Lithium metaborate/tetraborate fusion and dilute nitric acid digestion (Appendix 1). Total trace elements were analysed by inductively coupled plasma-mass spectrometry (ICP--MS; Appendix 2). Refractory elements underwent the same decomposition as the major elements (on an additional 0.2 g sample) while the rest are digested in hot Aqua Regia and analysed by the ICP-MS (0.5 g sample). Detection limits for major and trace-element are shown in Appendixes 1 and 2.

Eventually, trace-element distributions among rock-forming minerals, based on the partition coefficients of elements, were determined by geochemical fractional crystallisation modelling using the following equation (Shaw, 1970), shown as geochemical-mineralogical diagrams. Data of the partition coefficients for the different minerals used in the present paper are from Keskin (2005) and Ersoy and Helvacı (2010).

$$\frac{C_S}{C_0} = Df^{(D-1)} \qquad [1]$$

where: C_s and C_0 – element concentration in crystallised phase and initial liquid (different rock types in the layered gabbros) respectively, D – partition coefficient of element in crystallised phase relative to liquid, and f – remained liquid ratio during the crystallisation.

GEOCHEMISTRY

WHOLE ROCK GEOCHEMISTRY

Geochemical investigations reveal that all rock samples belong to a tholeiitic magma series (Fig. 4A). The existence of normative (C.I.P.W. norm – Cross, Iddings, Pirsson and Washington) quartz + hypersthene and olivine in most samples support their olivine tholeiite nature. Given the Sm/Yb vs. La/Sm diagram (Fig. 4B) all rocks studied might have been generated from a spinel lherzolite mantle source by mostly equilibrium melting. Comparison of the samples studied with different types of gabbro from subduction zones show that layered and massive gabbros are low-K tholeiite and medium-K calc-alkaline in composition (Fig. 5), respectively.

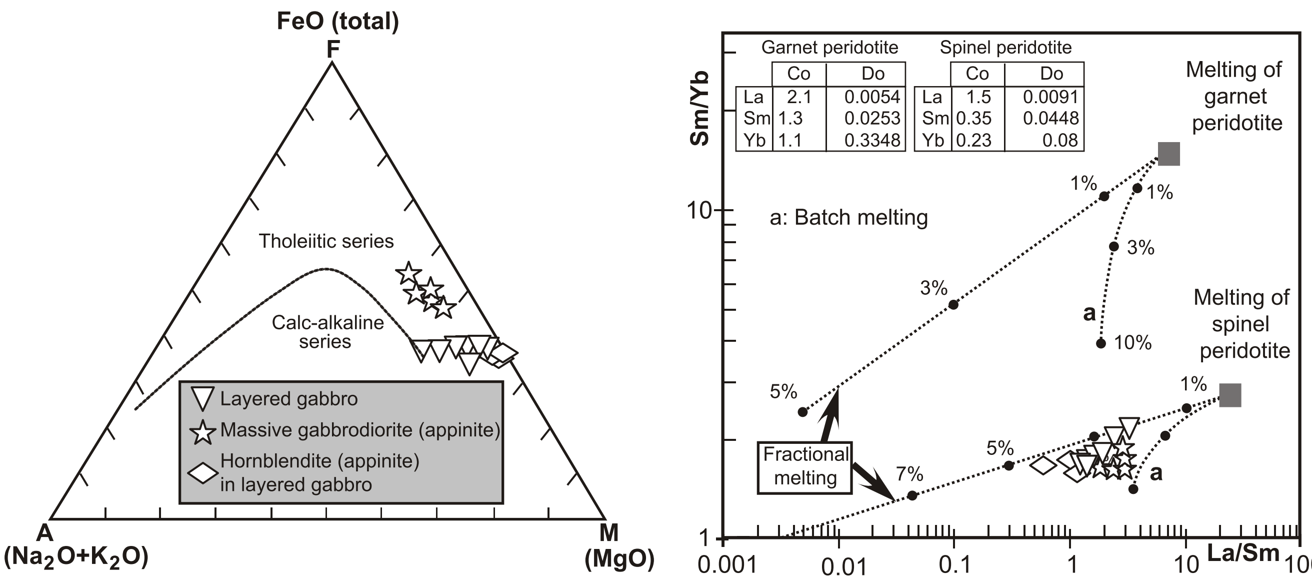

Fig. 4A – AFM triangular diagram which indicates that all samples plot in the tholeiitic magma series field; B – La/Sm vs. Sm/Yb diagram showing theoretical equilibrium and non-equilibrium melting curves for rocks with garnet lherzolite and spinel lherzolite source (Keskin, 2005); the Mingol-Mamakan gabbroic samples are placed in the field of equilibrium melting with a spinel lherzolite mantle source

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1339

LAYERED GABBROS

The Mingol-Mamakan mela-, meso-, and leuco-gabbros show wide ranges in MgO, Fe_2O_3*, CaO, and Al_2O_3 content (Appendix 1). Amounts of MgO and Fe_2O_3* in the layered gabbros are lower than in the hornblendites (appinite) of the layered gabbros and massive gabbrodiorites (appinite). All rock types of layered gabbros have lower contents of K_2O in comparison with massive gabbrodiorites. There are increasing levels of SiO_2, Al_2O_3, CaO, Na_2O, and K_2O and decreasing levels of FeO*, MgO, and MnO from gabbros towards clinopyroxene-bearing anorthosites.

Concentrations of Sr in the leuco-gabbros are higher than in meso- and mela-gabbros. By contrast, concentrations of Co, Cr, and Ni in the leuco-gabbros are lower than in meso- and mela-gabbros. High concentrations of Sr and Ba are related to high contents of Na_2O and CaO.

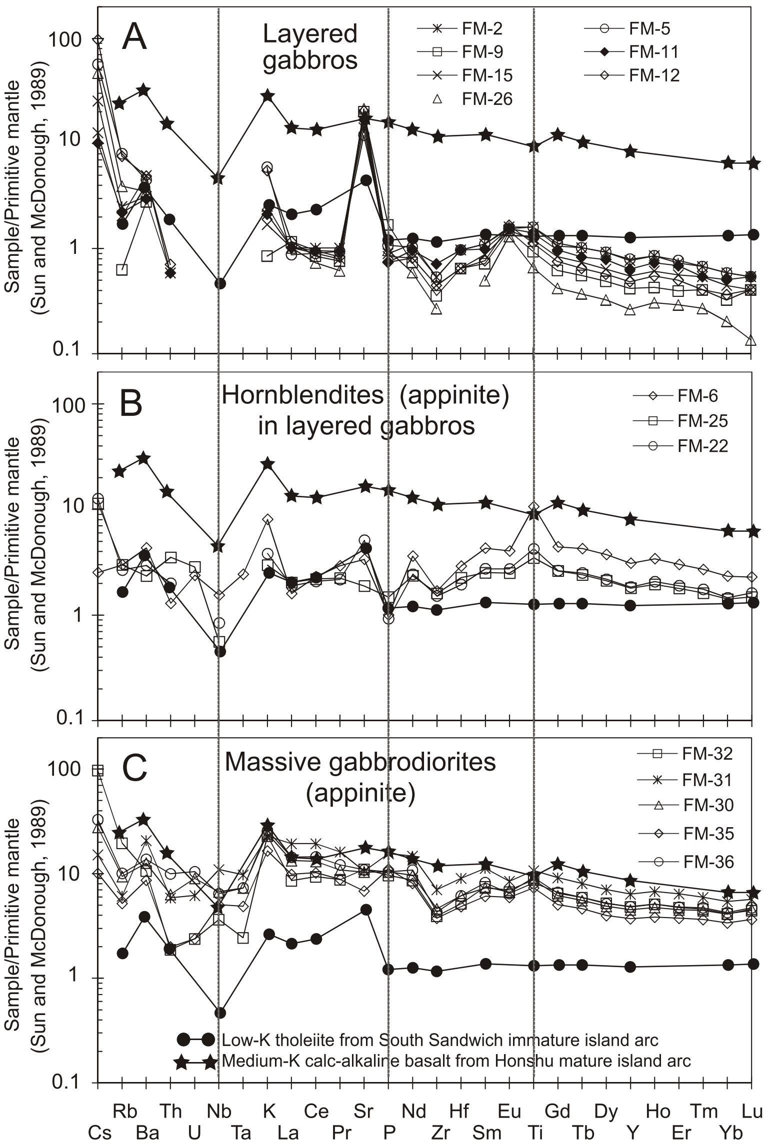

Fig. 5. Spider diagrams normalized to the primitive mantle (Sun and McDonough, 1989) for the Mingol-Mamakan gabbroic intrusions

A – multi-element spider diagrams for the layered gabbros; **B** – multi-element spider diagram for hornblendite (appinite) in the layered gabbros; **C** – multi-element spider diagram for massive gabbrodiorites which are appinitic in composition

The gabbros show positive Sr and Ba and negative Nb and P anomalies (Fig. 5A). The gabbroic rocks are not strongly enriched in LREEs (light REE; Figs. 5A and 6A). Therefore, there are low La_n/Yb_n ratios (Appendix 2) and flat HREE patterns in the gabbros (Figs. 5A and 6A). There are high Eu/Eu* ratios in leuco-gabbros (average 2.30) in relation to those in meso-gabbros (1.49) and mela-gabbros (1.39). These layered gabbros show negative Nb, Zr, and P anomalies.

HORNBLENDITE (APPINITE) IN THE LAYERED GABBROS

Hornblendite in the layered gabbros can be distinguished from other rock types based on their major element abundances. Contents of MgO, Fe_2O_3*, TiO_2, and MnO and Al_2O_3 in the hornblendites are different than in other rock types in the layered gabbros, respectively (Appendix 1). Contents of SiO_2 are similar to those in the massive gabbrodiorites. Contents of Fe_2O_3* and CaO in the hornblendites are similar to those in the massive gabbrodiorites. By contrast, only the contents of Na_2O and K_2O are similar to those in the layered gabbros. In the hornblendites, high contents of Fe_2O_3*, MgO, CaO, V, Cr, Co, and Ni and low concentrations of Sr (Appendix 1) are present.

Concentrations of Nb and Ta in the hornblendite follow similar trends. There are negative Nb, P, and Zr and moderately positive Ti anomalies in these rocks (Figs. 5B and 6B). By comparison, Eu shows no anomalies in the hornblendites. The La_n/Yb_n and Lan/Smn ratios range between 0.70–1.37 and 0.37–0.81. Also, the patterns (Figs. 5B and 6B) are not similar to those in the other rock types (Figs. 5A, C and 6A, C).

MASSIVE GABBRODIORITES (APPINITES)

There are lower concentrations of SiO_2, TiO_2, MgO, Fe_2O_3*, Na_2O, MnO, and K_2O and higher concentrations of CaO and Al_2O_3 in the layered gabbros compared to those in the massive gabbrodiorites. Contents of Fe_2O_3*, Na_2O, K_2O, and SiO_2 are higher than in the other rock types (Appendix 1). On the other hand, X_{Mg} is lower than in the other rock types. As for the layered gabbros, the massive gabbrodiorites are also related to a tholeiitic suite (Fig. 4A).

Compared to the layered gabbros, the massive gabbrodiorites have higher concentrations of V, Cr, Rb, Sr, Ba, and REEs. There are negative Ta, Zr, and Hf anomalies and slight positive or negative and/or no Nb anomalies (Fig. 5C). Additionally, high concentrations of P and Ti in the massive gabbrodiorites produce positive anomalies in the spider diagram.

The rocks show REE patterns as negative slopes from LREE to HREE. Therefore, La_n/Ybn and La_n/Sm_n ratios lie in ranges between 1.93–3.41 and 1.15–1.83. Additionally, the patterns (Fig. 5C) are not similar to those in the layered gabbros (Figs. 5A, C and 6A, C). Hence, total REEs in the massive gabbrodiorites are higher than in the layered gabbros.

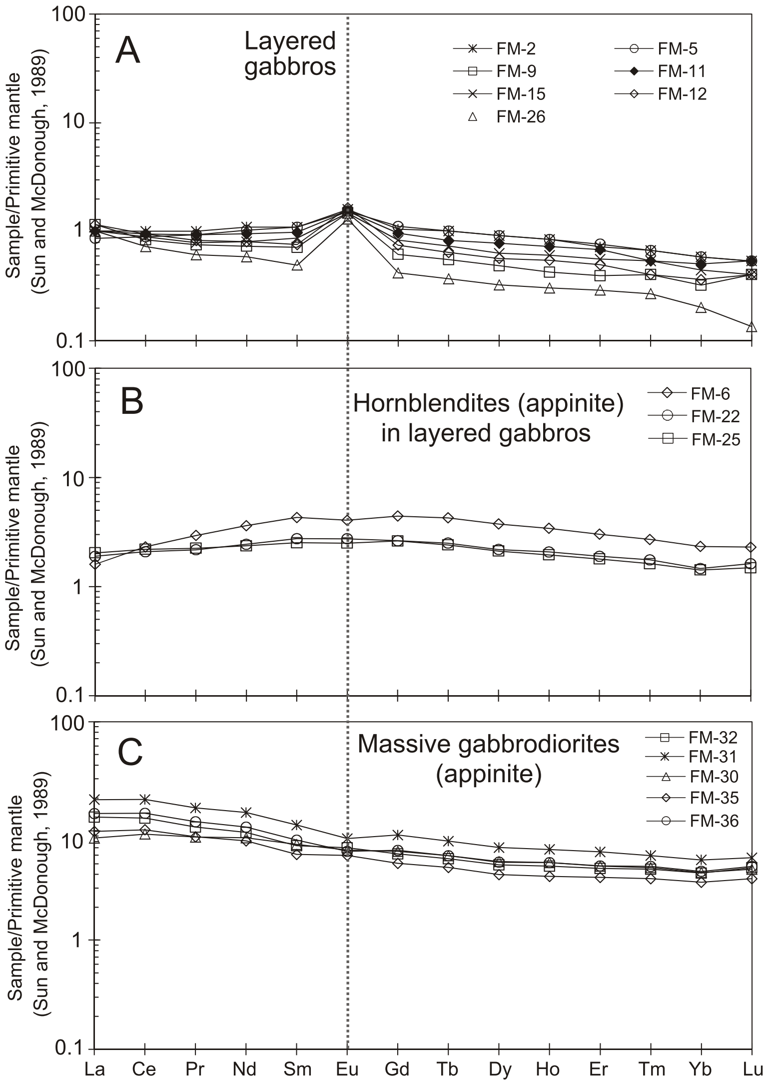

Fig. 6. Spider diagrams normalized to the primitive mantle (Sun and McDonough, 1989) for the Mingol-Mamakan gabbroic intrusions

A – REE spider diagrams for the layered gabbros; **B** – REE spider diagram for hornblendite (appinite) in the layered gabbros; **C** – REE spider diagram for massive gabbrodiorites which are appinitic in composition

CRYSTALLISATION

According to field and petrographic observations, all rock exposures in the layered and massive gabbros have the same ages. Such characteristics demonstrate that the rocks may have evolved in mechanical disequilibrium condition throughout their crystallisation in the magma chamber.

Geochemical-mineralogical modelling of the rocks studied indicates that various minerals have been involved in concentrations of incompatible trace-elements. Moreover, using a fractional crystallisation equation (Equation 1), the main factors for frequency distribution of the elements in each rock group were examined. Accordingly, the trace element concentrations are dominantly controlled by the main phases during fractional crystallisation which consist of pyroxene (clinopyroxene and orthopyroxene), plagioclase, amphibole, olivine, titanite and ilmenite. The phases were determined based on petrographic studies (Fig. 2) and C.I.P.W. norms (Appendix 1). Using "FC-modeler, *Microsoft® Excel©* Software" (Keskin, 2002), chemical modelling for variations of different elements was done and then, based on trace element partition coefficients, geochemical-mineralogical diagrams were drawn (Figs. 7–10).

Potassium (K) as a large ion lithophile element (LILE) is absorbed from the melt, probably by clinopyroxene, during crystallisation (Fig. 7A). The presence of abundant plagioclase and clinopyroxene crystals in the layered and massive gabbros-gabbrodiorites as well as in the hornblendites (approximately 3 to 8%) has probably been a factor as regards variations in concentration of this element. Barium (Ba, as LILE) is easily replaced instead of sodium or potassium in the octahedral position of hornblende and plagioclase (Fig. 7B). Additional ionic charge can be neutralized as a result of interchanges of aluminum and silicon. Plagioclase and hornblende in massive gabbrodiorites and hornblende in hornblendites, which both are appinite in composition, have been a factor as regards Ba concentration. By contrast, plagioclase in the layered gabbros has been the main factor for the variation of this element.

Rubidium (Rb) (as LILE) is replaced instead sodium or potassium in amphibole and probably in clinopyroxenes. However, in the rocks studied, the main concentrating phases of Rb are amphibole and plagioclase (Fig. 7C). Strontium (Sr) (as LILE) shows significant variations in all the rock types of Mingol-Mamakan. The hornblendites associated with the layered gabbros, display a much lower concentration than do the other rock types (Appendix 2). This low concentration is consistent with a lower modal percentage of plagioclase. But, in the layered and massive gabbros-gabbrodiorites, the concentration of Sr is higher, this increasing with an increase in modal percentage of plagioclase. Considering Figure 7D, plagioclase has been a major factor in the variation of Sr in all rock types of Mingol-Mamakan.

Rare earth elements (REE) are mainly absorbed by amphibole and clinopyroxene in all rock types studied (Fig. 8A). In addition, REE distributions display an adapted trend with plagioclase in the samples studied, indicating strong absorption of Y by plagioclase (Fig. 8B). A positive Eu anomaly (Figs. 5A and 6A) in the layered gabbros indicates the role of instability of plagioclase during partial melting (Fig. 8B). Therefore, plagioclase may have had an important role in this trend in the samples. By comparison, the lack of a Eu anomaly in the massive gabbrodiorites and in the hornblendites of the layered gabbros (compare Eu between Sm and Gd in Figures 5B, C and 6B, C) have led to weak correlation related to the plagioclase in the Eu/Y vs. Eu/Yb diagram (Fig. 8B). Hence, plagioclase might have played no significant role in the variation of Eu in these units.

The behaviour of high field strength elements (HFSE, such as Ta, Nb, Hf, and Zr), Th and U generally shows that amphibole and clinopyroxene have been important factors in controlling these elements during crystallisation (Fig. 9). Significant negative anomalies of HFSE along with a negative anomaly of P (Fig. 5), suggest that subduction may have involved in the evolution of the Mingol-Mamakan rocks. A spinel lherzolite ori-

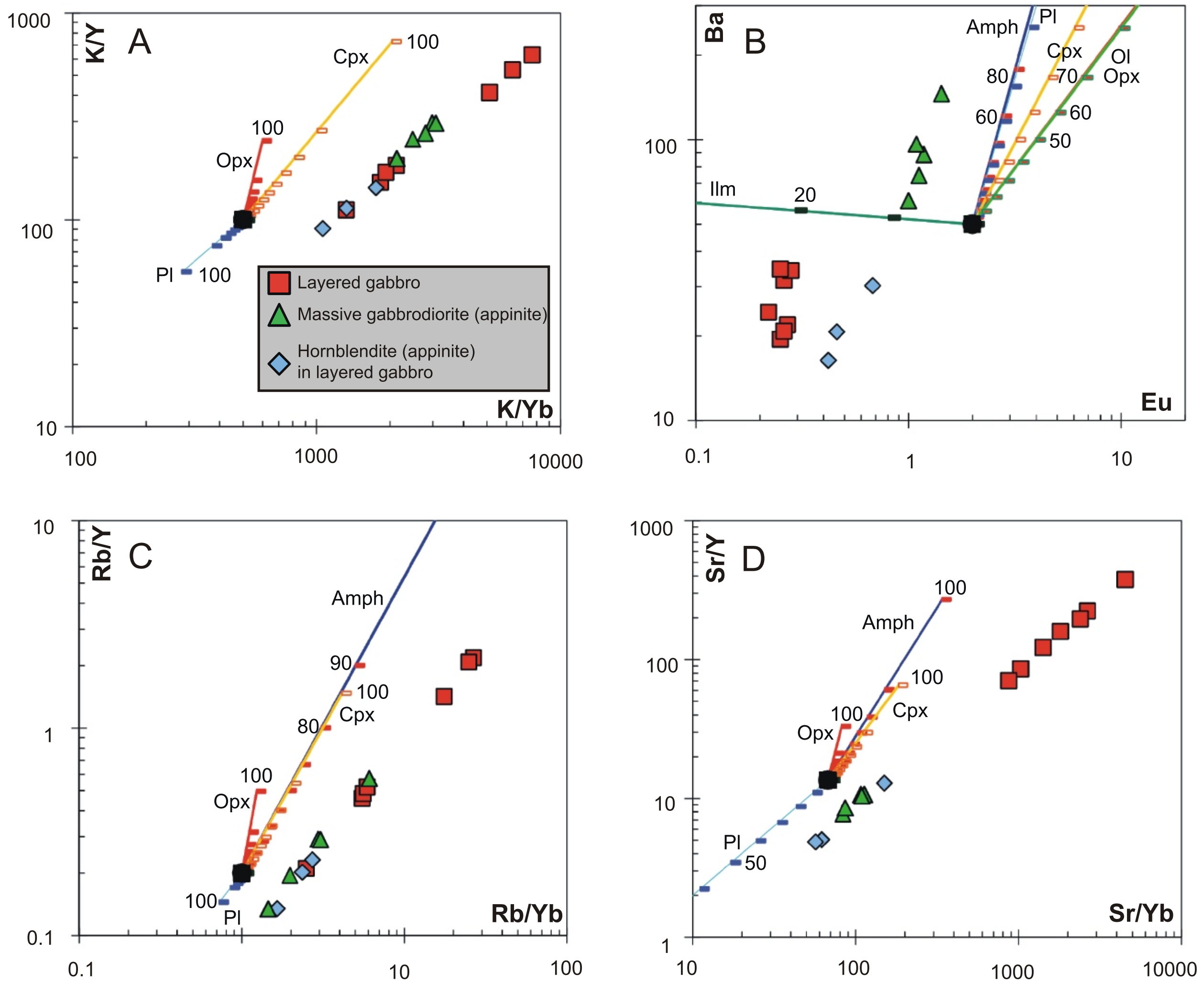

Fig. 7. Chemical diagrams for determination of phases absorbing LILE from the Mingol-Mamakan gabbroic-appinitic rocks

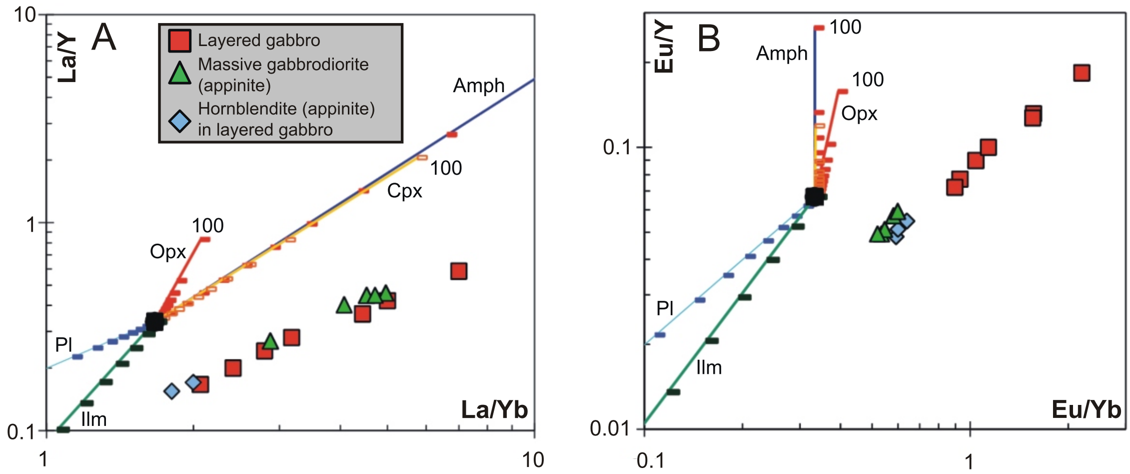

Fig. 8. Chemical diagrams for determination of phases absorbing REE from the Mingol-Mamakan gabbroic-appinitic rocks

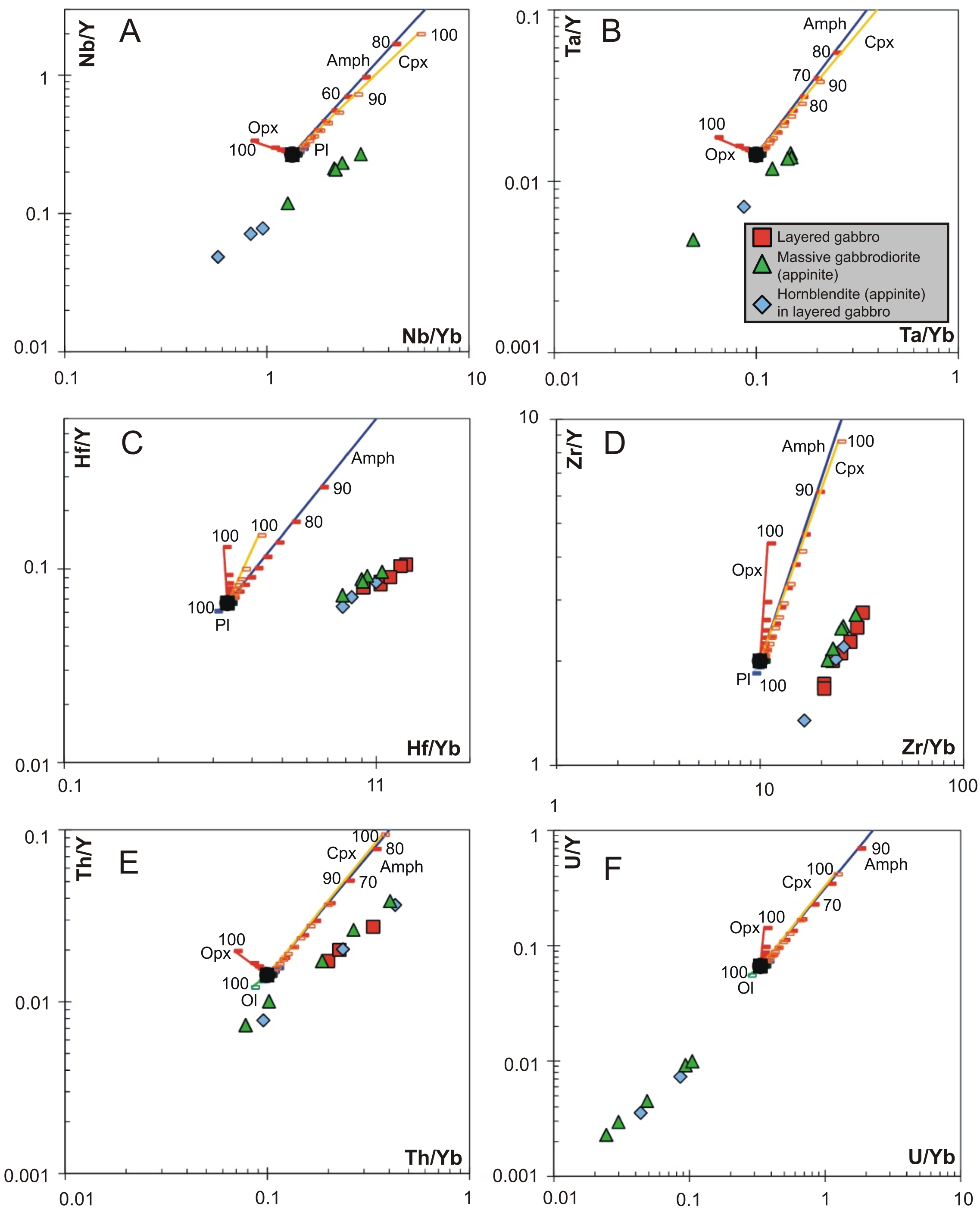

Fig. 9. Chemical diagrams for determination of phases absorbing HFSE from the Mingol-Mamakan gabbroic-appinitic rocks

gin of the Mingol-Mamakan gabbros (Fig. 4B) indicates that the stability of spinel could have been an important factor for the depleted nature of this group of elements during partial melting. Moreover, the immobile and incompatible nature of HFSE demonstrates that they are unable to transfer by metasomatic fluids into the mantle wedge.

Geochemical-mineralogical modelling of transitional elements of the periodic table (Fig. 10) such as Ni, Co, V, Cr, and Ti indicate that ferromagnesian minerals such as clinopyroxene, orthopyroxene, amphibole, and olivine have been the main controlling factors of these elements. Ni and Co are mainly absorbed by olivine and orthopyroxene and probably by clinopyroxene and amphibole in much smaller amounts (Fig. 10A, B). Essentially, the Ni ion is similar to the Mg ion in terms of charge and ionic radius and thus it is replaced in ferromagnesian minerals. However, Ni can be replaced instead of ferrous iron. Therefore, a ferrous iron-bearing clinopyroxene can also absorb Ni according to Figure 10. Co can be easily substituted instead of the ferrous iron of ferromagnesian minerals. V can be easily replaced instead of ferric iron in clinopyroxene due to a valence of +3 ions (Fig. 10C). Given the diagram of V/Yb vs. V/Y (Fig. 10C) clinopyroxene has been an important absorbent

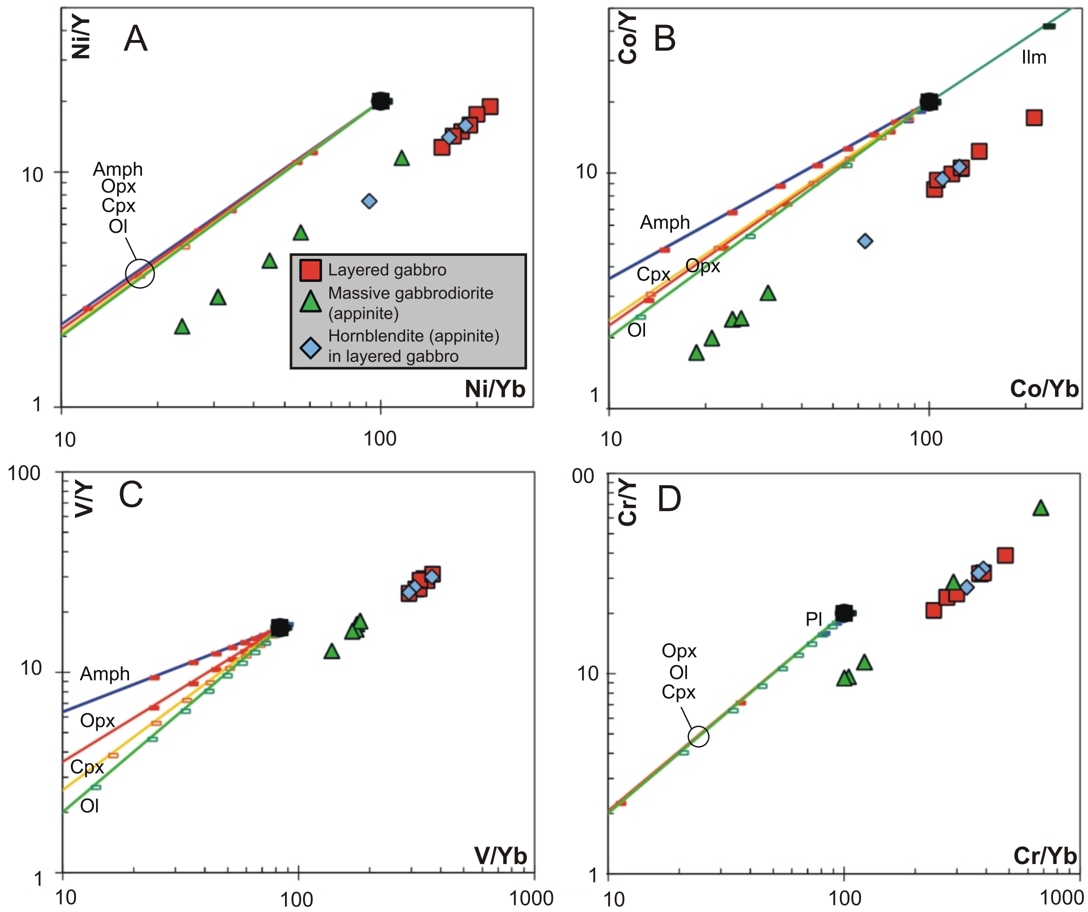

Fig. 10. Chemical diagrams for determination of phases absorbing transition metals from the Mingol-Mamakan gabbroic-appinitic rocks

of V. Cr similarly to V has a valence of +3 and thus can be replaced instead of ferric iron in clinopyroxene (Fig. 10D). The lack of this type of iron in olivine and orthopyroxene lead these minerals to have no Cr absorption.

TECTONIC SETTING

Comparison of field observations and geochemical and isotopic age data (Asadpour, 2012) of the Mingol-Mamakan gabbroic-appinitic complex with low-K tholeiitic basalt from the South Sandwich immature island arc (Pearce et al., 1995; Gill, 2010) and the medium-K calc-alkaline to tholeiitic basalt from the Honshu mature Island arc (Pearce et al., 1995; Gill, 2010) shows that the complex has probably been an active subduction system during the interval from 322 Ma (Late Carboniferous) to 300 Ma (Early Permian) (Fig. 11). At this time the Palaeotethys oceanic lithosphere may have subducted to the edge of the Mingol-Mamakan supra-subduction oceanic crust which probably was connected to the edge of the Paleozoic platform of Central Iran (Fig. 11A). Comparison of geochemical data between the Mingol-Mamakan gabbroic units and the low-K tholeiites from South Sandwich (Fig. 5A; see the lower part of Figure 5C) reveal that the Mingol-Mamakan layered gabbros were probably formed in an immature island arc setting (at 322–314 Ma; Fig. 11). In contrast, comparison of geochemical data between the Mingol-Mamakan massive gabbrodiorites and medium-K calc-alkaline to tholeiitic basalt from the Honshu Island (Fig. 5C) indicates that massive types might have generated in a more mature island arc setting in the Early Permian (at 300.7 ±1.5 Ma; Fig. 11).

Occurrence of magma mingling between the massive gabbrodiorites and the granitic rocks (Fig. 2A) possibly reflects real continental crust at the time of massive gabbrodiorite magma injection. Subsequently, granitic magmas might have formed via partial melting of crustal source by injecting hot gabbroic magmas beneath the mature island arc crust. All available evidences indicate that subduction of Palaeotethys beneath the Mingol-Mamakan Island arc led to formation of layered and massive gabbros-gabbrodiorites between 322 Ma (Late Carboniferous) and 300 Ma (Early Permian).

APPARENT SITUATION FOR PARTIAL MELTING

By comparison, gabbros of the layered gabbros show a positive Eu anomaly (Figs. 5A and 6A) in contrast to hornblendites (appinites) of the layered gabbros which demonstrate no Eu anomaly. This suggests that these two parts are supposedly co-genetic but may have formed by melting under different conditions, or with different plagioclase differentiation.

Accordingly, gabbroic magma was generated as a result of instability of plagioclase during partial melting of source rocks.

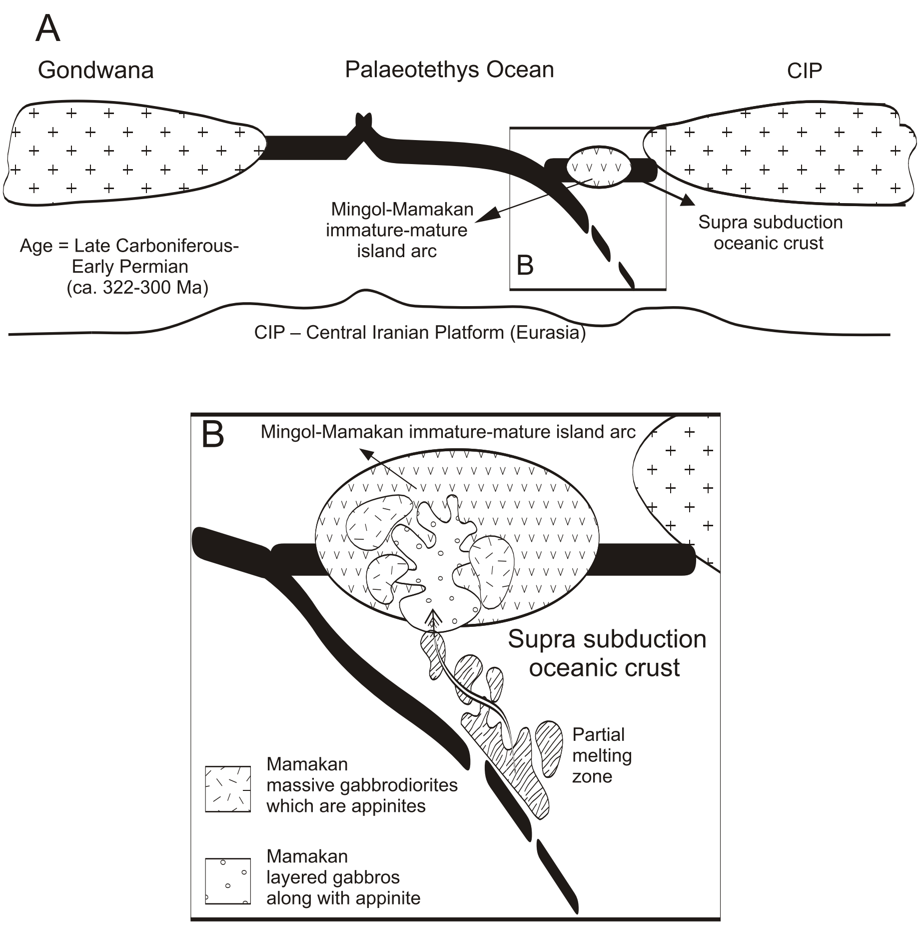

Fig. 11. Tectono-magmatic evolution of the Mingol-Mamakan gabbroic-appinitic intrusions

A – formation of Mingol-Mamakan Island arc; **B** – formation of massive and layered gabbros-gabbrodiorites in the edge of Central Iranian Platform supra subduction zone

At the same time the most likely source of the water-rich hornblendite component, would have been the result of metasomatism of a plagioclase-free mantle, synchronously injected with gabbroic units. Also with regard to Figure 4B, plagioclase could not have been present as a sustained phase in mantle melt production. Therefore, it is probable that these two distinct parts of layered gabbros formed in different parts of the mantle (Fig. 12). Figure 12 demonstrates that point c can be a suitable place for tholeiitic layered gabbro magma production in arc environments (see tectonic setting section). Most likely, this shallow area with a high degree of partial melting has been an apparent site for production of the Mingol-Mamakan tholeiitic layered gabbros. According to Figure 12, the size of area affected by partial melting is larger. In addition, heat accumulation in this area led to an increase in the geothermal gradient and a higher degree of partial melting (Gill, 2010).

The tholeiitic massive gabbrodiorites might have formed as a result of lower degrees of partial melting and an older subduction age (Asadpour, 2012), indicating a greater depth of subduction. The massive gabbrodiorites, which are actually appinites, contain large amounts hydrous phases such as hornblende relative to gabbros of the layered gabbros. Thus, it is probable that these massive gabbrodiorites were generated from a plagioclase-free mantle metasomatised deep source. A lower degree of partial melting is consistent with greater depths of melting and the lack of Eu anomaly in these rocks (Mysen, 1988). Hence, it is likely that point b (Fig. 12) was a suitable place for partial melting. Accordingly, melts produced in shallow parts of the mantle have undergone different evolutionary processes by fractional crystallisation on ascending to crustal levels, generating massive and layered gabbros-gabbrodiorites with various modal percentages of mafic and felsic minerals and consequently a diversity of gabbro lithology.

The Mingol-Mamakan appinite-gabbro suites preserve a visible record of the role of water in magma genesis, transport, emplacement and crystallisation (also see Fazlnia and Alizade, 2013). This suite is a group of coeval plutonic rocks, ranging from ultramafic to intermediate in composition in which hornblende is the dominant mafic mineral and occurs as megacrysts and in the matrix. The dominance of hornblende and textural evidence for rapid growth of coarse-grained minerals is visible in the field (Fig. 2). Evidence of a high volatile content in the magma includes:

– the abundance of hornblende as both megacrysts and in the matrix (Fig. 2),
– evidence of pegmatitic texture,
– the occurrence of complex leucogabbros and appinites (Fig. 2D),
– the presence of water-rich magma (mafic) lenses as enclaves into the water-poor magma (A-type granite) in the Mingol-Mamakan intrusions.

These lines of evidence are supported by many experimental investigations which indicate that with an increase in pH_2O (1) the stability field of hornblende expands relative to those of olivine, pyroxene and plagioclase (e.g., Yoder and Tilley, 1962; Moore and Carmichael, 1998; Müntener et al., 2001; Grove et al., 2002, 2005) and (2) the melt becomes depolymerised (e.g., Mysen, 1977, 1988), thereby reducing its viscosity, and this facilitates rapid hornblende growth in pegmatitic rocks (see Murphy, 2013 for more discussion). Based on Murphy (2013) the magma chamber may become less water-rich at depth implying a potential gradation from appinite suite rocks near the roof of a pluton to more conventional olivine-pyroxene gabbros at depth. Therefore, a water-rich magma (mafic magma) would facilitate the occurrence of hornblende as a dominant mafic mineral. Rapid ascent of magma along deep-seated faults would be accompanied by decompression during which the solubility of water in the magma may be exceeded. The water released water would be expected to rise towards the roof of the chamber. The origin of the water in the Mingol-Mamakan intrusions is metasomatised mantle in the supra-subduction zone (Fig. 11B). Therefore, fluid

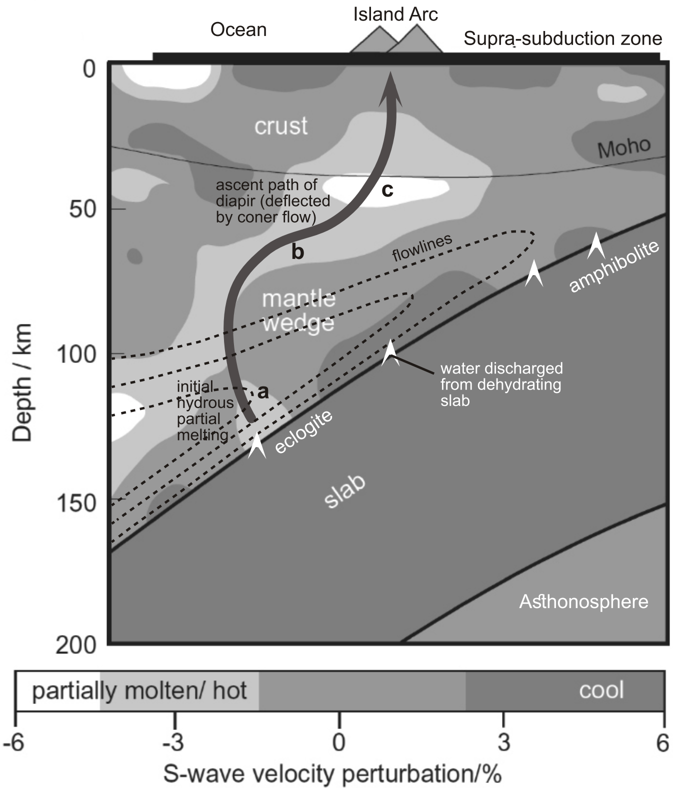

Fig. 12. Possible location of mantle melting for Mingol-Mamakan layered and massive gabbrodiorites (modified after Gill, 2010)

Points b and c – the most probable locations for generation of massive and layered gabbros-gabbrodiorites, respectively; point a, with garnet lherzolite composition, could not possibly be the location for generation of rocks

and the crystallisation of amphibole played an important role in changes of various elements in the suite.

CONCLUSIONS

The Mingol-Mamakan massive and layered gabbro-appinite suite is a large intrusion at the northwest edge of the Central Iran Platform and reflects an Island-arc environment. The intrusions were probably formed in an immature-mature island arc setting as a result of Palaeotethys oceanic crust subduction beneath the supra-subduction zone and partial melting of a spinel lherzolite mantle wedge source at ~320–300 Ma. Geochemical studies indicate that massive and layered gabbros-gabbrodiorites formed via partial melting in two different parts of the mantle wedge, at deeper and shallow melting sites respectively, from a water-rich primary tholeiitic basalt magma which underwent fractional crystallisation to form intrusive rocks in the lower crust. The abundance of elements in various Mingol-Mamakan rock types were mainly controlled by variable amounts of common minerals such as amphibole, plagioclase, and clinopyroxene. In addition, refractory phases in the mantle wedge and at the time of magma evolution in crustal levels caused variations in major and minor elements.

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