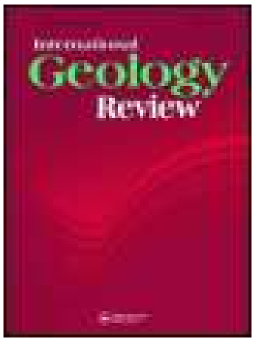

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Physical and chemical interactions between coeval magmas: a case study of mixing and mingling from the Urumieh plutonic complex, NW Iran

Amin Jafari[a,b], Ian S. Williams[b], Mohsen Moayyed[a] and Susan Jamei[b,c]

[a]Department of Earth Sciences, Faculty of Natural Sciences, University of Tabriz, Tabriz, Iran; [b]Research School of Earth Sciences, Australian National University, Canberra, Australia; [c]Faculty of Earth Sciences, Shahid Beheshti University, Tehran, Iran

ABSTRACT

Field observations, whole-rock geochemistry, mineral chemistry and zircon U-Pb dating results from microgranular mafic enclaves and their host syenite, Urumieh plutonic complex, NW Iran, show that the enclaves and host are coeval, genetically related and evolved by synchronous magma mixing–fractionation. Geochemically all belong to the shoshonitic series and probably originated from the same enriched subcontinental mantle-derived magma in a subduction setting. SHRIMPU-Pb dating of zircon from representative samples of host rocks and enclaves yields mutually indistinguishable late Cretaceous crystallization ages, 90.7 ± 1.3 and 91.3 ± 1.1 Ma (host syenite), and 90.2 ± 0.7 and 91.6 ± 0.7 Ma (enclaves). Pressure and temperature estimates from Al-in-amphibole and amphibole-plagioclase pairs from both host and enclaves suggest that the interacting magmas mixed and crystallized under similar P-T conditions at middle crustal levels (average 662–716°C and 2.2–2.8 kbar). The occurrence of hybrid to mafic enclaves along with disrupted mafic dikes indicates a long-lived mafic source with multiple replenishments throughout the crystallization history of the complex, and large variability in viscosity within the magmatic system. The transition from mixing to mingling depends on the different crystalline states of the interacting magmas, especially the host magma, which strongly influence rheological properties. In the liquid-liquid state, mixing typically will continue until complete hybridization. With increasing polymerization and crystal load in the host magma, magmatic relationships change progressively from chemical mixing to more mechanical mixing (mingling), producing distributed mafic enclaves, then disrupted mafic dikes, then syn-plutonic mafic dikes as a continuum given sufficient time.

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Syenite; magma mixing; magma mingling; mafic enclave; U–Pb dating; geochemistry

1. Introduction

Magma mingling and mixing are recognized as processes operating in many magmatic systems worldwide. The concept of magma mixing as a geological process was first proposed in 1851 by the chemist Robert Bunsen, who interpreted the intermediate lava compositions in Iceland as resulting from the binary mixing of trachytic and basaltic magmas (Bunsen 1851). Magma mixing has subsequently played an increasingly important role in petrogenetic models for co-genetic suites of igneous rocks from a wide variety of tectonic settings. A general consensus from innumerable studies (e.g. Barbarin and Didier 1992; Poli *et al*. 1996; Blake and Fink 2000; Sun *et al*. 2010; Shimizu *et al*. 2016; Suzano *et al*. 2017) is that such rocks represent interaction principally between two different magmas. Magmatic interaction processes have been widely studied in both plutonic and volcanic environments (e.g. Thomas and Tait 1997; Blake and Fink 2000; Perugini and Poli 2012) and mixing is accepted as one of the major processes affecting compositional variability of igneous rocks and the production of intermediate composition magmas (e.g. Hibbard 1981; Anderson 1982; Sparks and Marshall 1986; Wiebe 1994; Perugini and Poli 2005; Reubi and Blundy 2009; Kent *et al*. 2010). These interactions occur either at a deep crustal level related to crustal contamination and/or magma mixing with crustal melts, or by magma mingling and local mixing at the emplacement level, but the conditions and mechanisms of the interactions remaincontroversial. Evidence of magma mixing/mingling is found, in particular, in plutonic bodies and can be observed over a range of scales, from whole pluton down to single crystals.

The interaction between mafic and felsic magmas can result in magma mingling, magma mixing, or mingling combined with mixing. The term 'mingling' (or partial mixing) is widely used in the overwhelming majority of publications to describe a mechanical interaction between coexisting magmas of different

CONTACT Amin Jafari a.jafari9291@gmail.com Department of Earth Sciences, Faculty of Natural Sciences, University of Tabriz, Tabriz, Iran
Supplemental data for this article can be accessed here.

compositions with no chemical exchange, whereas 'mixing' involves chemical exchange, as a result of which the physical and chemical identities of the magmas are changed, producing relatively homogeneous hybrid rocks (e.g. Barbarin and Didier 1992; Flinders and Clemens 1996; Sklyarov and Fedorovsky 2006; Perugini and Poli 2012; De Campos 2015).

The concept of magma mixing is now widely accepted and has evolved towards maturity, but less effort has been spent trying to give a precise definition of magma mingling. Perugini and Poli (2012), for example, believed that mingling is a rare process. The difference between mingling and mixing needs to be specified, even though it is sometimes not easy to discriminate clearly between the two. In plutonic settings magmatic mafic microgranular enclaves (MMEs) are one of the most common indicators of the interactions between magmas, especially mingling. Commonly the outer rinds of MMEs are fine-grained, have sharp contacts with the host, and are enriched in mafic and hydrous minerals such as hornblende and biotite relative to the coarser grained centre of the enclave. This strongly suggests that the migration of fluids or fluid influx has been involved, and that chemical transfer of some mobile elements would be inevitable during or after the mixing process by diffusion, volatile transfer or metasomatic processes under near-solidus or sub-solidus conditions (e.g. Eberz and Nieholls 1990; Vernon 1990; Holden *et al*. 1991; Perugini *et al*. 2003; Farner *et al*. 2014). With numerous studies indicating that at least some chemical exchange takes place in the contacts between two contrasting magmas during this process, the concept of magma mingling should not be limited to physical interaction alone. Furthermore, MMEs should not be confused with xenoliths that represent extraneous pieces of angular rocks fragment derived from the older country rocks, incorporated into the magma chamber either during magma ascent or emplacement. Although, xenoliths frequently show some evidence of reaction, e.g. rounding of their edges, metamorphism, and -recrystallization textures (Didier and Barbarin 1991), MMEs can be easily identified from those via structural and textural evidence as provided in the present work.

In this paper, we provide structural and textural evidence that magmas interacted in the study area. The field relations, petrography, mineral and whole-rock geochemistry and zircon geochronology of both enclaves and host rock are closely examined and a model proposed for magma mixing and mingling.

2. Important factors in a plutonic mixing system

Felsic magmas that are derived in a wide variety of ways, including the fractionation of a more mafic parent, crustal contamination and or partial melting of various crustal rocks such as meta-sedimentary and meta-igneous rocks, may have physical and chemical properties in common, but are quite different from mantle-derived mafic magmas. The simple mixing of different magmas from source materials of different compositions therefore is not necessarily possible. The extent to which juxtaposed magmas blend or mix depends critically on the differences in their rheological properties and their relative proportions (Sparks and Marshall 1986).

Due to the large variety of relevant factors involved in contrasting magmas, the degree and style of mixing that takes place in a magma chamber and the consequent shape and size of enclaves will be diverse and complex. The most important factors that affect the rheological behaviour of more evolved magmas in a plutonic system include their viscosity, density, temperature, chemical composition (especially H_2O and silica contents), crystal contents and relative volumes (e.g. Barbarin and Didier 1992; Perugini and Poli 2012). Each of these factors, alone or in combination, can limit wide-scale mixing and hybridization, such that if magmas are to mix completely they must have similar properties. The time available for interaction between contrasting magmas is important – homogenization and equilibration of crystals between dissimilar batches of magma takes longer (Barbarin and Didier 1992; Best 2003). Another obstacle to mixing is the very low diffusion rates of chemical species in silicate liquids. Chemical diffusion is faster at higher temperatures and in melts with low viscosity (Winter 2001). If co-existing magmas develop a stable interface, any mixing is limited to the very slow process of diffusion across that interface.

The most important property of melts that controls the dynamic behaviour of magmas is viscosity. The viscosity ratio between co-existing fluids is important in determining the type of instabilities that develop at the interface, which in turn has a bearing on the mixing. Viscosity is strongly affected by volatiles. Dissolved water significantly decreases melt viscosity (Dingwell *et al.* 1996), affecting the fraction of crystals present at a given temperature, which in turn affects magma viscosity (Champallier *et al.* 2008; Picard *et al.* 2011). Small (several percent by mass) concentrations of water have a dramatic effect in lowering the viscosity of silicate liquids. For example, the addition of 2 wt% H_2O to a granitic melt lowers the melt viscosity by a factor of 10^5 (Lesher and Spera 2015). H_2O also tends to lower the viscosity of more mafic compositions, although the effect is less dramatic because fewer bridging oxygens are present in anhydrous mafic melts (Lesher and Spera 2015). Injections of hot, H_2O-poor magma can increase the reservoir temperature, leading to the dilution of melt H_2O contents (Cassidy *et al.* 2016).

The viscosities of basaltic to rhyolitic magmas and their intrusive equivalents range from 10^1 to 10^8 poise (Takeuchi 2001). The viscosity of mafic magmas is generally many times less than that of felsic magmas due to their high temperature, and low silica, volatile and crystal contents. Moreover, mafic magmas have higher density than felsic magmas, mainly because mafic magmas are typically richer in heavy oxides such as MgO, CaO and FeO, whereas felsic magmas are richer in lighter oxides such as SiO_2, Al_2O_3, and Na_2O (Frost and Frost 2013). The density of felsic to mafic magmas ranges from about 2.2 to 3.1 g/cm^3 and rises with increasing pressure; it falls with increasing temperature (Frost and Frost 2013). Strong viscosity and density contrasts encourage co-existing magmas to form a stratified system, impeding intimate contact between them and limiting interaction.

3. The Urumieh plutonic complex

The Urumieh plutonic complex, part of the Sanandaj-Sirjan magmatic-metamorphic belt, occupies about 700 km^2 in northwestern Iran (Figure 1). Thecomplex consists of several igneous bodies that intrude Permian to Jurassic sediments, mainly limestones and shales, and is locally covered by Early Miocene formations. The plutonic rocks range in composition from mafic to felsic, including gabbro, diorite, syenite and granite, all of which were generated in response to subduction of Neo-tethyian oceanic crust beneath the central Iran

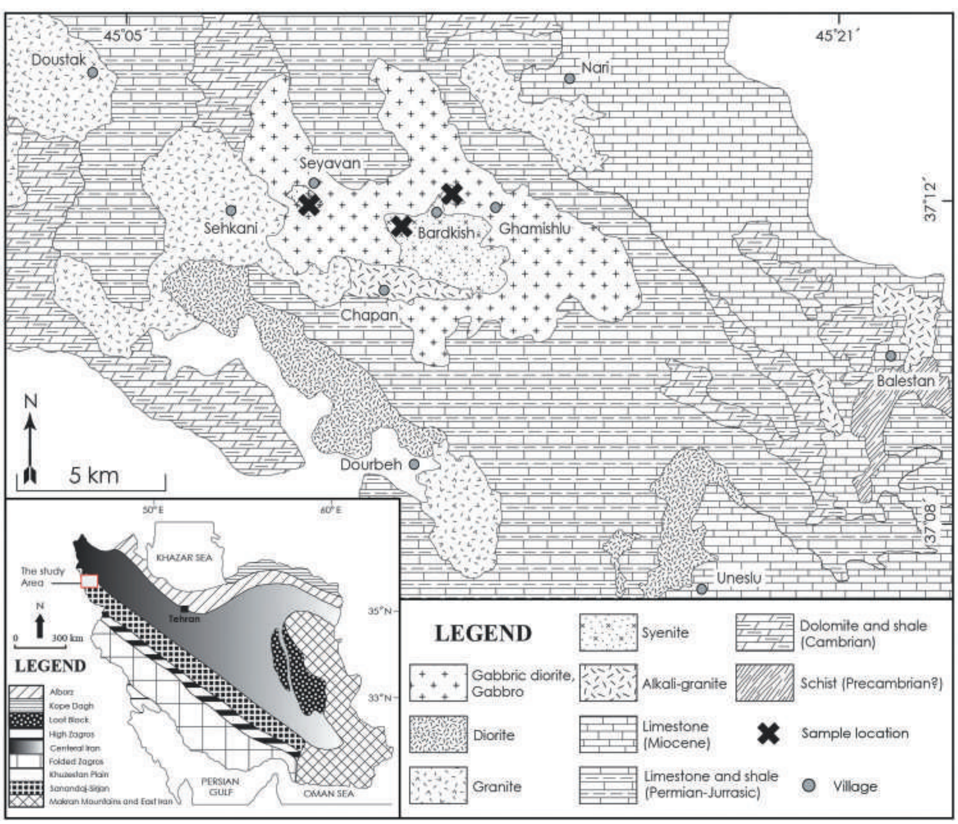

Figure 1. Sketch geological map of the study area and major geological subdivisions of Iran after Stöcklin (1968)

plate during the Mid-Late Cretaceous (Ghalamghash *et al*. 2009; Jafari *et al*. 2018). The major components of the complex are mafic and do not contain enclaves or xenoliths. The granites contain only a few metasedimentary xenoliths in some places. MMEs are common in the syenitic unit, however, and it is the interaction between that unit and the surrounding mafic components that bears directly on the processes of magmatic mixing and mingling

3.1. Mixing and mingling processes inferred from field relations

There is extensive evidence for magma mixing and mingling in the Urumieh complex, with extremely varied morphologies of mafic-felsic interfaces exhibited by mafic magmatic enclaves, hybrid enclaves and synplutonic mafic dikes. Such variations reveal the differences in rheological behaviour between the mafic and felsic magmas at different stages of their interaction. The

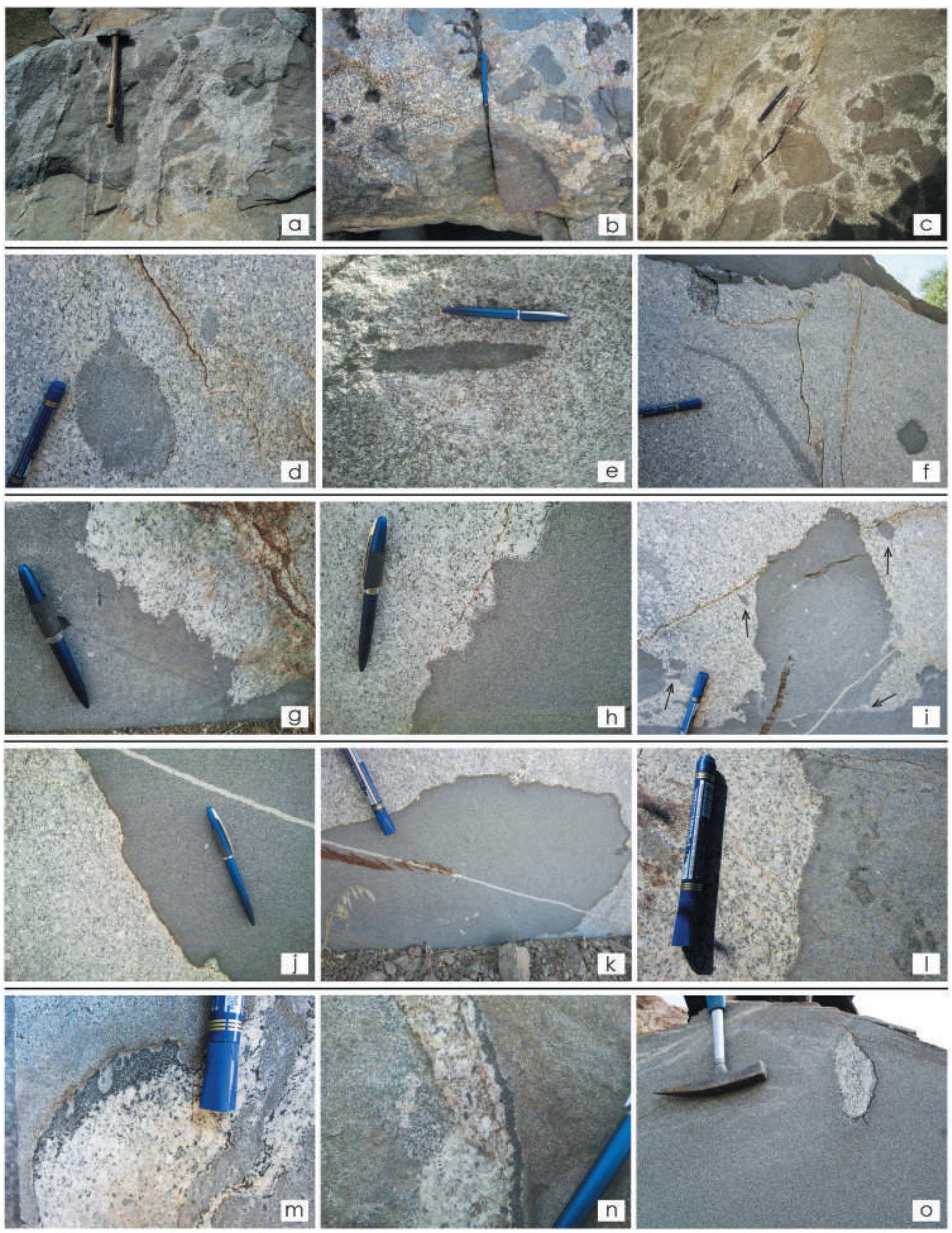

Figure 2. (a, b, c) A mixed population of mafic to hybrid enclaves of various shapes and sizes. (d, e, f) Moderately to highly stretched elliptical to lenticular MME and trails of mafic schlieren formed under the influence of relative flowage of MME and host magmas during homogenization. (j, h, i) Fingering structures indicating initial stages of intrusion of mafic magma into the felsic host. The ‘fingers’ can become detached to form enclaves (indicated by arrows). (j, k, l) Fine-grained chilled rims enriched in mafic and hydrous minerals and an enclave with a non-enriched rim. (m, n, o) Generation of a thick rim enriched in mafic minerals when host magma is encountered by a large volume of mafic magma and/or dropped into it.

enclaves, which occur in swarms or scattered through the host syenite, range in size from centimetres to metres, and in shape from rounded to ellipsoidal, discoidal, lenticular, tabularand diverse elongated forms (Figure 2(a–c)). This diversity of enclave shapes is likely to reflect the variation in the viscosity of the interacting magmas, and the time available for deformation and differential strain during the mixing process (Pitcher 1991; Barbarin and Didier 1992; Arvin *et al*. 2004). Numerous trails of oriented enclaves and schlieren structures delineate magmatic flow in the syenite (Figure 2 (d–f)). Schlieren are most common in the hybrid enclaves, in which MME mixed with the host felsic magma. Enclaves with flow structures probably developed prior to complete solidification of the syenite, possibly due to convective flow in the magma chamber (Didier and Barbarin 1991; Wiebe and Collins 1998; Vernon 2004; Arvin *et al*. 2004).

Contacts between the mafic and felsic facies are varied, from curved and smooth to extremely irregular, with fingers of the mafic magma penetrating into the felsic host (Figure 2(g–i)). Finger structures are attributed to the initial stage of mafic magma intrusion into felsic magma (Perugini and Poli 2005). At the interface between two contrasting magmas, at the time of active interaction, double-diffusive instability driven by two different density and temperature gradients takes place at different diffusion rates (Turner and Campbell 1986). The diffusive interface develops unstable boundary layers due to the more rapid diffusion of heat, which leads to viscous fingering at the boundary of the turbulent fountain. 'Fingers' of magma can be detached from the main stock and form smaller enclaves (Figure 2(g–i)).

The MMEs, regardless of morphology or size, are characterized by thin chilled rims, commonly enriched in mafic constituents (biotite and amphibole) and depleted in felsic minerals. The rims range from non-enriched rims, to enriched rims a few millimetres wide (Figure 2(j–l)), to thicker margins enriched in mafic minerals (Figure 2(m–o)), and diffuse or gradual contact surfaces (Figure 3(a–c)). When felsic magma incorporates a globule of hot mafic magma (both in a partly liquid state), the mafic magma is quenched to the temperature of the cooler host. This induces chemical diffusion across the quenched contacts (Bussy 1990), so that nucleation rates of precipitating mafic silicates increase because of

Figure 3. (a, b, c) MMEs with irregular shapes with partially to completely diffuse contact with the host syenite. (d, e, f) Early-formed feldspar phenocrysts from the host intruding into the hybrid and mafic enclaves. (g, h) Disrupted and fragmented syn-plutonic mafic dikes intruding into the partially crystallized host syenite.

rapid loss of heat and a relatively fine-grained rim is produced (Vernon 1990). The marked difference in temperature between felsic and mafic melts (700–800 cf.-1100–1300°C) means that the felsic melt behaves as a coolant for hot or even overheated mafic melts (Sklyarov and Fedorovsky 2006). The general lack of chilled margins on enclaves indicates that the interacting magmas had such a small difference in temperature that neither was chilled when they came into contact, suggesting that such enclaves at the time were in near to completely solid state.

When the felsic host magma encounters a large volume of mafic magma, the thickness of the chilled margins on the enclaves increases because the cooling rate is slower, forming larger crystals (Figure 2(m–o)). Generating a chilled margin is controlled by the differences in crystalline state and temperature between the interacting magmas, and also the volume of injected mafic magma. Partially to completely diffuse boundaries between enclave and host represent a transitional stage between mingling and mixing processes. This feature is a sign of approaching thermal and chemical equilibrium between the mafic and felsic magmas and is a prelude to complete mixing (Figure 3(a–c)).

K-feldspar phenocrysts are commonly observed within MMEs, and they are especially abundant in the hybrid enclaves (Figure 3(d–f)). These commonly have been interpreted as mechanically transferred crystals from host to enclaves (e.g. Barbarin and Didier 1992; Kumar *et al*. 2004), which would imply only a small rheological difference between the two magmas, such that transportation of crystals was possible. Alternatively, the phenocrysts might be the products of diffusion reactions, not the result of physical mixing (Lundstrom 2005).

There are many syn-plutonic mafic injections that have been moderately to highly disrupted to form angular to sub-rounded MMEs (Figure 3(g,h)). Disruption of syn-plutonic mafic dikes within the host depends upon the stages and degrees of felsic magma crystallization (Collins *et al*. 2000). Chilled margins, and also cuspate to lobate contacts between the syn-plutonic mafic dikes and syenite host, indicate that hot mafic magma was injected into relatively cool crystallizing felsic magma in a partly molten state, resulting in mechanical interaction.

3.2. Petrographic evidence for magma mixing

The rock units examined in the present study of mixing processes have been classified based on their quartz-plagioclase-alkali feldspar modal mineralogy (Streckeisen 1973) as syenite (host), monzonite (hybrid enclave) and gabbro to monzo-gabbro/diorite (mafic enclave).The following area range of features in the host and enclaves that are inferred to be the result of magma interaction.

Composition: Both the enclaves and host generally contain the same mineral assemblage, but in different proportions. They typically have a porphyritic hypidiomorphic granular texture and are mainly composed of alkali feldspar, plagioclase, biotite, amphibole and quartz. Accessory minerals include apatite, titanite, zircon, and opaque minerals. Sericite, epidote, and chlorite are present as secondary phases. The similarity in the composition of equivalent minerals in the enclaves and the host is evidence for magma mixing (Vernon 1990; Barbarin and Didier 1992).

Alkali feldspar: Alkali feldspar is distributed unevenly and has three distinct morphologies. The first type is fine grained and restricted to the ground mass in the host rock. The second type consists of alkali feldspar phenocrysts from the host which appear to have penetrated mechanically into the mafic and hybrid enclaves before the entire system solidified (Figure 4(a)). The composition of the mafic or hybrid enclaves is chemically unsuitable for the precipitation of K-feldspar phenocrysts at an early stage of their crystallization. Hence these crystals have been transferred from the host magma (Vernon 1990, 1991). Because of the relatively strong chemical contrast between the two magmas, phenocrysts crystallized in the host and mechanically transferred into enclaves will not be in equilibrium with the new conditions (Barbarin and Didier 1992). This can cause some phenocrysts to dissolve partially or entirely, and become mantled by minerals in equilibrium with the surrounding magma (Vernon and Paterson 2008) (Figure 4(b)). The third type occurs in both the host and enclaves as larger crystals with poikilitic, and occasionally perthitic, textures and some resorbed margins (Figure 4(c)).

The last stages of crystallization of the magmas were dominated by large crystals of quartz and/or K-feldspar (c.f. Collins *et al*. 2000). Mixing of coeval mafic (enclave) and felsic host magmas can induce the exchange of elements between them, such that CaO, MgO and FeO_t from the mafic magma are introduced to the felsic magma, resulting in the crystallization of mafic silicates, and conversely, SiO_2, K_2O, and Na_2O from the felsic magma are introduced to the mafic magma, resulting in the crystallization of quartz and K-feldspar (Barbarin and Didier 1992). Under such conditions, nucleation of quartz and K-feldspar may be delayed until the temperature falls sufficiently following the growth of mafic minerals (Vernon 1990). Following quenching, the remaining melt cools and crystallizes slowly, resulting

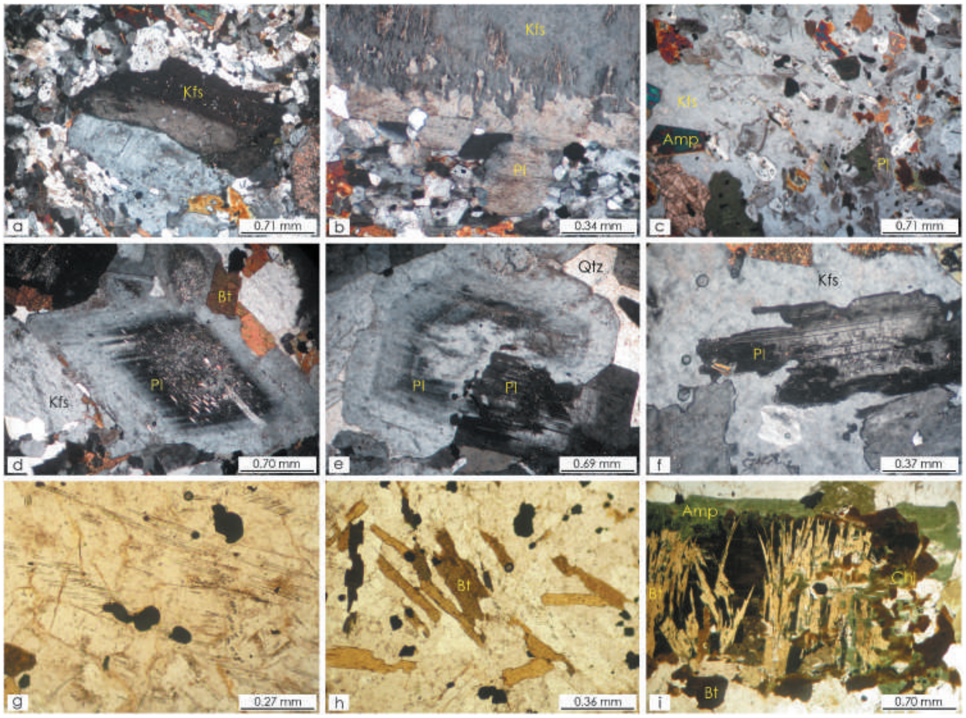

Figure 4. (a) Alkali-feldspar phenocryst belonging to the felsic host magma now in an MME. (b) Alkali-feldspar phenocryst with a partly dissolved margin generated under non-equilibrium conditions then mantled by plagioclase. (c) Poikilitic alkali feldspar enclosing small inclusions of early-formed plagioclase, hornblende, and apatite. (d, e, f) Normally-zoned plagioclase crystals with evidence of sericitization. Partial resorption or dissolution surfaces of early-formed plagioclase from the host magma. Evidence of interaction with hotter mafic magma.(g) Acicular apatite crystals in parallel extinction and prismatic crystals of apatite. (h) Oriented bladed biotite grains reflecting the rapid cooling of hot mafic magma intruded into cooler host felsic magma. (i) Hornblende–biotite–titanite clots in MME.

in the formation of some large grains of quartz and K-feldspar that poikilitically include earlier-formed crystals (Hibbard 1991).

Plagioclase: Plagioclase occurs in both the host and enclaves as euhedral to subhedral crystals of different sizes. These have normal zoning with evidence of sericitization (Figure 4(d)). Some crystals have non-equilibrium textures such as resorption surfaces, identified by discontinuous, truncated, and curved zones (Figure 4(e,f)). Resorption textures in plagioclase are commonly interpreted to indicate changes in plagioclase stability brought about by magma mixing, due to the high-temperature interaction of injected mafic magma into the host granitoid (Hibbard 1981).

Acicular and stubby apatite: Acicular (needle-shaped) apatite crystals are common in the mafic and hybrid enclaves, whereas the apatite in the felsic host mostly has a stubby habit. The acicular apatite has parallel extinction (Figure 4(g)). Highly elongate acicular apatite has been shown to result from rapid growth in a quenched mixed system (Wyllie *et al.* 1962; Hibbard 1991). The presence of different apatite morphologies in enclaves and host is another texture indicative of magma mingling and mixing (Hibbard 1991).

Bladed biotite: This unusual morphology of biotite, highly elongated in one direction, is typically observed in the enclaves (Figure 4(h)). Bladed biotite is evidence for physically restricted rapid growth in undercooled conditions, which the enclaves would have experienced in the magma mixing process (Hibbard 1991; Jeen *et al.* 2002).

Mafic clots: Clots of mafic minerals occur in the host and commonly in the hybrid and mafic enclaves (Figure 4(i)). They might be the result of primary pyroxene crystals reacting with the residual melt to form hornblende and/or biotite following thermal equilibration between the hot, relatively dry mafic, and the cool, relatively wet felsic, magmas (Vernon 1990; Baxter and Feely 2002).

4. Analytical methods

Nineteen un-weathered representative samples of host rocks and enclaves with minimal effects of late hydrothermal alteration were selected for analysis. Eight rock samples (prefix AJ), after being chipped by hand-splitterand powdered in a tungsten-carbide ring mill to a grain size of <200 μm, were sent to the ALS laboratory, Brisbane Australia, and eleven cut samples (prefix CJ) were sent to the Acme laboratory, Vancouver Canada, for whole rock geochemical analysis. ALS determined the major element oxide concentrations using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) following the lithium borate fusion method (detection limit of 0.01%) and trace element concentrations using Inductively Coupled Plasma Mass Spectrometry (ICP-MS-detection limit 10–0.01 ppm). Acme determined the major and trace element compositions using ICP-MS, with similar detection limits. The chemical compositions are reported in supplementary file 1.

Electron microprobe (EPMA) analyses of alkali-feldspar, plagioclase, biotite and amphibole in both host and enclaves (intermediate and mafic) were performed using a Cameca SX100 electron microprobe at the Iran Mineral Process and Research Centre (IMPRC). Analytical conditions were 15 kV accelerating potential, 20 mA beam current and electron beam diameter of 3 µm. The instrument was calibrated using natural and synthetic minerals as standards. The detection limit for oxide species was 100 ppm. Representative mineral analyses are listed in supplementary file 2.

Two samples of host syenite (AJ-3 and AJ-9) and two of enclaves (AJ-15 and AJ-17) were selected for zircon U-Pb dating. The U-Th-Pb isotopes were analysed using the SHRIMP-RG at the Research School of Earth Sciences (RSES), Australian National University (ANU), following the analytical procedure described by Williams (1998). U concentration was calibrated relative to standard zircon SL13 (238 ppm U) and Pb/U determined relative to reference zircon TEMORA 2 (417 Ma; Black *et al*. 2004). The radiogenic isotope ratios and calculated ages were corrected for common Pb using the measured ^{207}Pb, assuming concordance and a model common Pb composition consistent with the age of the grain (Cumming and Richards 1975) using Prawn and Lead software written by Ireland (1998). All individual dates and weighted mean ages were calculated from the radiogenic $^{206}Pb/^{238}U$. Data were plotted using Isoplot 3 (Ludwig 2003), showing the analyses before correction for common Pb. For all analyses, the uncertainty in the determination of Pb/U and Pb/Th was set to a minimum of 0.5% to prevent the high precision analyses of high-U spots skewing the calculation of the weighted mean ages. The results are summarized in supplementary file 3.

5. Results

5.1. Whole-rock compositions

The chemical compositions of representative samples of mafic and hybrid enclaves and their host are given in supplementary file 1. The host rocks are of intermediate composition (SiO_2 = 60.7–-63.4 wt.%), and the enclaves of intermediate to mafic composition (SiO_2 = 42.68–59.7 wt.%). The host rock plot in the syenite domain and enclaves lie in the gabbro to monzonite fields on the total alkali-silica (TAS) classification diagram (Figure 5(a)). The whole set of samples has a high-K to shoshonite character in K_2O vs. SiO_2 (Figure 5(b)) and Ce/Yb vs. Ta/Yb (Figure 5(c)). Their high Na_2O+K_2O contents, low TiO_2 and variable Al_2O_3 also satisfy the criteria for shoshonite as proposed by Morrison (1980). Their aluminium saturation index, with A/CNK (molar Al_2O_3/CaO+Na_2O+K_2O) ratios from 0.66 to 1 and A/NK (molar Al_2O_3/Na_2O+K_2O) ratios from1.1 to 2.1 (Maniar and Piccoli 1989) indicate that they are metaluminous. Low A/CNK, and the lack of typical peraluminous minerals (e.g. cordierite, andalusite and garnet) or alkaline mafic minerals (e.g. arfvedsonite, riebeckite and aegirine-augite), demonstrate that all facies are typical I-type granitoids (Liu *et al*. 2013).

All rocks have mostly coherent curvilinear trends in Harker diagrams, which points to the involvement of fractional crystallization. CaO, MgO, TiO_2, Fe_2O_3, V, Co, Y and Sr contents show a negative correlation with SiO_2, whereas the abundances of Al_2O_3, K_2O, Rb, Ba and Zr are positively correlated. Concentrations of P_2O_5, Na_2O and Nb are relatively scattered, possibly as a result of the magma mixing process. Compared with the host syenite, the hybrid and mafic enclaves have higher TiO_2 (1.38–3.78 wt.%), CaO (4.07–10.50 wt.%), MgO (2.01–6.20 wt.%), Mg# (31.30–59.46) and similar Al_2O_3 content (15.90–-17.85 wt.%). Primitive mantle-normalized rare earth element (REE) patterns for both host and enclaves are marked by the absence of a Eu-anomaly (Eu/Eu* = 0.8–1.45), moderate enrichment in the light REEs (LREE) and less fractionated heavy REEs (HREE) (Figure 6(a)). La_N/Sm_N ratios for the host syenite, hybrid, and mafic enclaves are in the range 6.9–-13.45, 4.7–8.3 and 3.31–4.26 respectively, while Gd_N/Yb_N ratios range from 1.60 to 1.86, 1.18 to 2.33 and 2.00 to 2.17 respectively. Considering multi-element spider diagrams (Figure 6(b)), both host and enclaves are enriched in the large ion lithophile elements (LILE; e.g. Rb, Ba, K and Cs) relative to the high field strength elements (HFSE; e.g. Th, U, Zr and Hf), but they differ in the relative enrichments and depletions in some other elements. The host syenite has marked depletions in Ta, Ti, Nb, Sm, P and Pb, while Ba, Pb and Sm depletions are more pronounced in the hybrid and mafic enclaves.

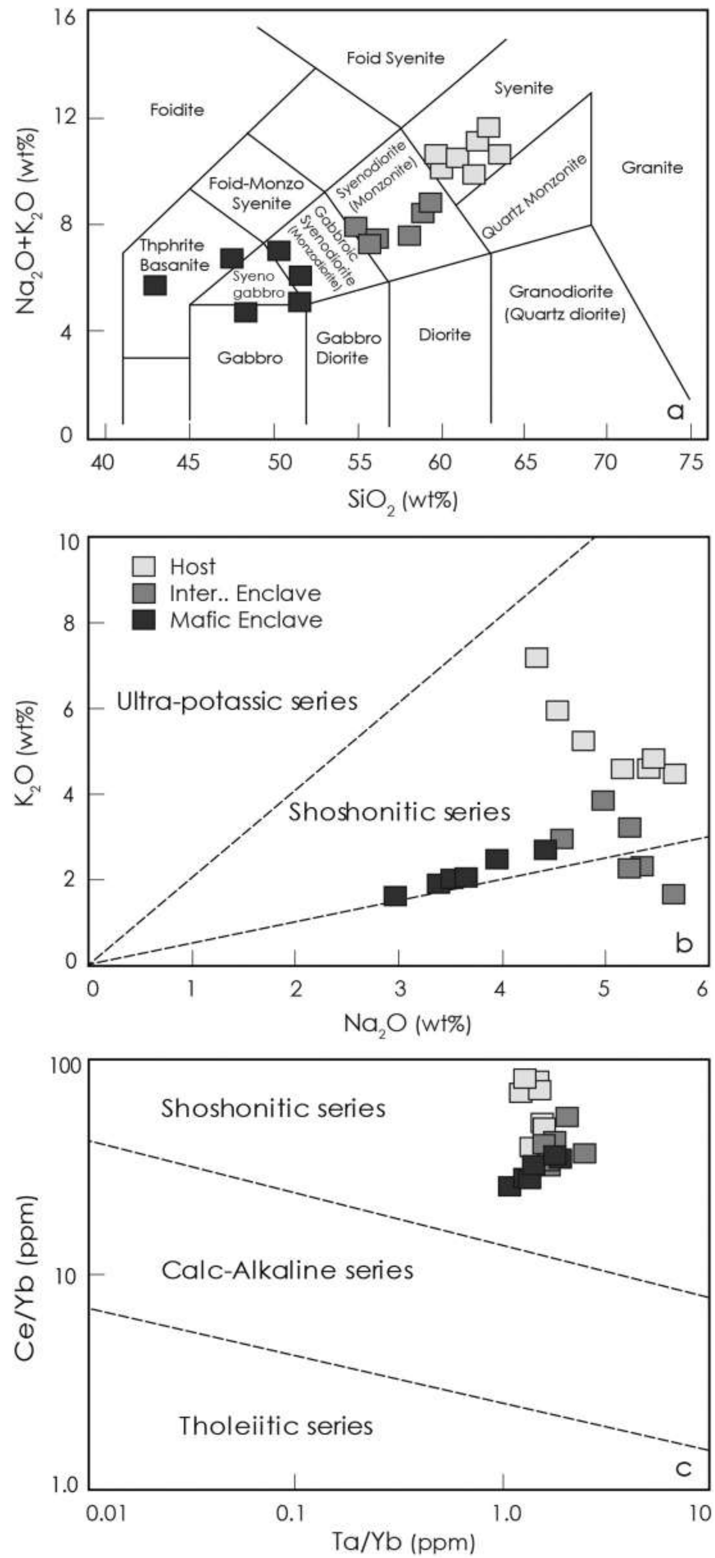

Figure 5. (a) Alkali-Silica diagram (TAS) for the chemical classification of plutonic rocks (Le Bas *et al*. 1986). (b) K_2O vs. SiO_2 (Gill 1981) and (c) Ta/Yb vs. Ce/Yb (Pearce 1983) diagrams indicating the shoshonitic affinity of all lithologies.

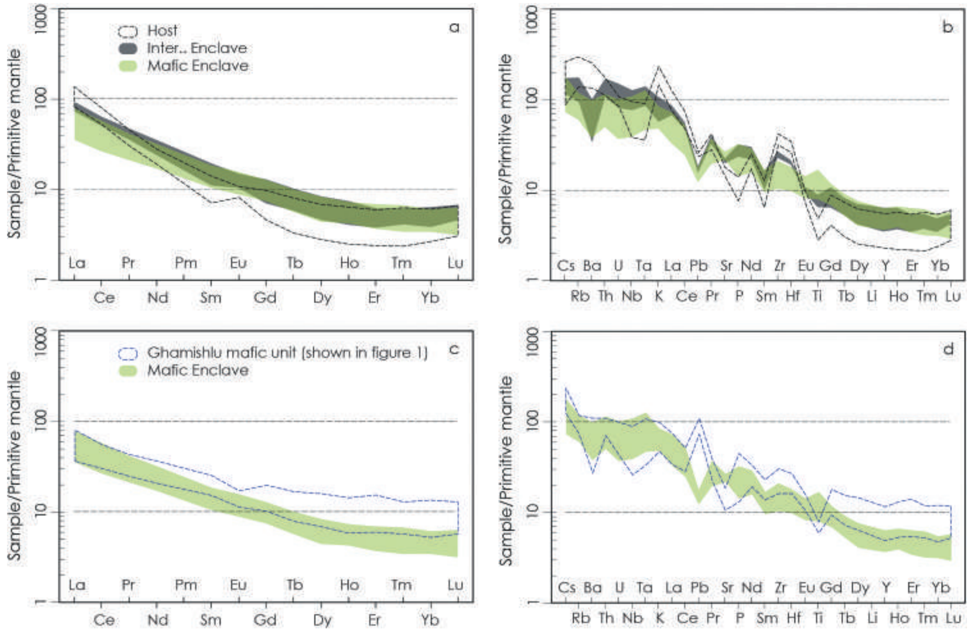

Figure 6.. (a) Primitive mantle normalized REE compositions and (b) Primitive mantle-normalized multi-element patterns. Normalizing values from .McDonough and Sun (1995) and Sun and McDonough (1989) respectively. Ghamishlu mafic unit data is from Ghalamghash *et al*. (2013).

5.2. Mineral compositions

5.2.1. Alkali-feldspar

The alkali feldspar in all rock types is orthoclase; host syenite (Or_{87-94}), hybrid enclave (Or_{83-90}) and mafic enclave (O_{93-98}), with K_2O ranging between 13 and 16 wt.% in the host and 15 and 16 wt.% in the enclaves. Both host rock and enclaves show no significant distinction between K-feldspar compositions and no compositional zoning was detected within the individual crystals.

5.2.2. Plagioclase

The plagioclase phenocrysts in all rock types are sodic, with a core of andesine surrounded by a shell of oligoclase; host syenite (Ab_{68-78} An_{18-29}), hybrid enclave ($Ab_{62-78}An_{17-35}$) and mafic enclave ($Ab_{64-79}An_{15-33}$). Matrix plagioclase in all facies shows same compositional variations and has identical Na-rich rims. There is no important difference in plagioclase zoning style (core-rim variations) between host rock and enclaves, indicating a relatively stable chemical composition and uniform conditions during plagioclase crystallization.

5.2.3. Amphibole

All amphiboles from the host, intermediate and mafic enclaves are calcic (Ca_B>1.5) and magnesio-hornblende in composition (classification of Leake *et al*. 1997). The amphiboles are enriched in Mg and depleted in Fe, with Mg/(Mg+Fe) and Fe/(Fe+Mg) ratios ranging from 0.58 to0.72 and 0.28 to 0.42 respectively. In comparison with the host syenite, the enclave amphiboles have generally higher MgO (host 2.2–2.3, enclaves 2.5–2.8 wt.%), although they have overlapping compositions with respect to Al, Ti, Na, Si, K and Ca contents. The average of $Fe^{3+}/(Fe^{3+}+Mg)$ in the host rock (0.26), hybrid (0.24) and mafic (0.21) enclave amphiboles is higher than 0.2 (Anderson and Smith 1995), suggesting crystallization at high fO_2.

5.2.4. Biotite

The biotite in the host rocks and their enclaves has fairly similar chemical compositions in SiO_2, FeO, Al_2O_3, K_2O and TiO_2. $Fe^{2+}/(Fe^{2+}+Mg)$ is also in the same range, 0.51–0.57, indicative of the annite-rich biotite subgroup (Tischendorf *et al*. 1997). The similar iron-enrichment index and chemical compositions of biotite in the host syenite and related enclaves indicates that the biotite in both could be entirely equilibrated. The biotites in all facies have MgO, FeO_t and Al_2O_3contents consistent with crystallization in a subduction-related calc-alkaline environment (Abdel-Rahman 1994)

5.3. Geochronology

5.3.1. Host syenite

The results of ion microprobe U-Th-Pb isotopic analyses of zircon from samples AJ-3 and AJ-9, as representative of the host syenite, are listed in supplementary file 3. Zircon CL (cathodoluminescence) images and U-Pb isotopic compositions are shown graphically in Figures 7(a,

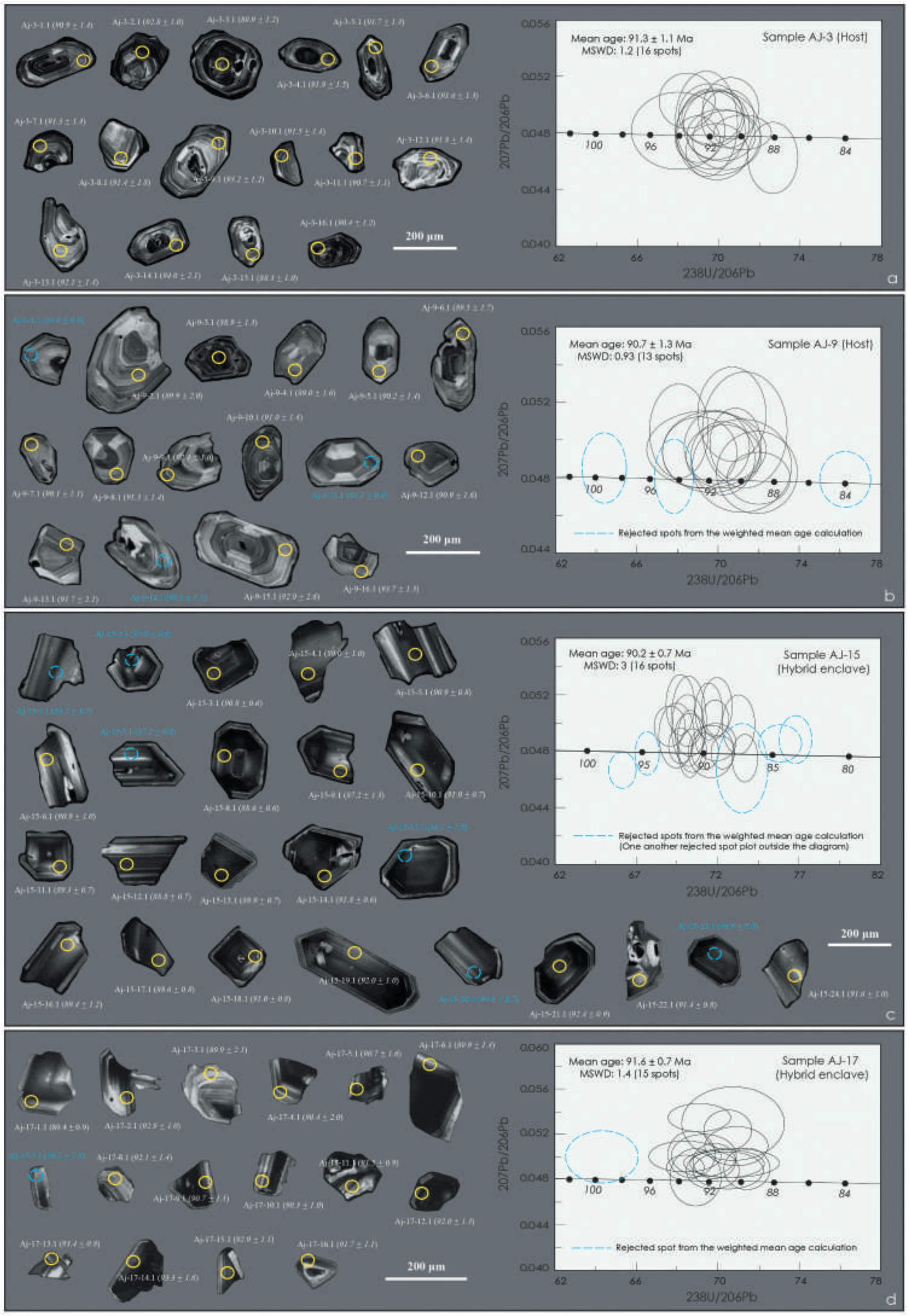

Figure 7. Representative zircon Cathodoluminescence (CL) images of analysed spots and U–Pb Concordia diagrams from host rock (a and b) and hybrid enclaves (c and d) analysed by ion microprobe. Isotopic compositions plotted without correction for common Pb. Analytical uncertainties 1 s.e. Analyses in blue not included in the age calculations.

b). Zircon grains from the two samples have many similarities. They are mostly euhedral to subhedral, medium to large (150–250 µm diameter), colourless to brown crystals with a prismatic habit and well-developed fine oscillatory zoning typical of growth under magmatic conditions. Apatite and melt inclusions are common. A few crystals are characterized by a CL-dark core and brighter rim with faint oscillatory zoning, consistent with the presence of an older core. Sixteen crystals from each sample were dated.

The zircons from sample AJ-3 have low to moderate U (240–1090 ppm) and Th (160–900 ppm) contents, with Th/U between 0.46 and 0.90. Common Pb contents are very low (a few ppb), so even without common Pb correction the U-Pb analyses plot on concordia within analytical uncertainty (Figure 7(a)). Radiogenic $^{206}Pb/^{238}U$ in all spots, even one CL-dark core, is the same within analytical uncertainty (MSWD = 1.2), giving a weighted mean age of 91.3 ± 1.1 Ma (95% c.l., which includes the uncertainty in the analysis of the standard). The zircon grains from sample AJ-9 have a similar range in composition (U 300–660 ppm, Th 170–630 ppm, Th/U 0.51–1.01), except for the one analysed core, in which the U and Th contents are significantly higher (U 1800 ppm, Th 1375 ppm). Most analyses are concordant within analytical uncertainty (Figure 7(b)), but there is significant scatter in the radiogenic $^{206}Pb/^{238}U$ (MSWD = 9.4). The scatter is due to two major outliers (one high and one low), and one subtle high outlier (AJ-9-14.1). None of the outliers is the analysis of the single dated core. Omitting the outliers leaves 13 determinations of radiogenic $^{206}Pb/^{238}U$ that are equal within analytical uncertainty, the weighted mean of which yields an age of 90.7 ± 1.3 Ma (MSWD = 0.93).

5.3.2. Hybrid enclaves

Two samples of hybrid enclaves, AJ-15 and AJ-17,were selected for zircon U-Th-Pb dating. The analytical results are listed in supplementary file 3. Zircon CL images and U-Pb concordia diagrams are shown in Figures 7(c,d). The zircon grains from sample AJ-15 are euhedral to subhedral and 100–200 μm diameter (Figure 7(c)), while those from sample AJ-17 are smaller (50–150 μm diameter), most with partially dissolved anhedral shapes (Figure 7(d)). All grains are transparent and colourless to light brown. Apatite and melt inclusions are common. Most grains are weakly zoned and are characterized by a polyhedral CL-dark centre that is generally relatively homogenous, overgrown by a narrow CL-light rim that has broad oscillatory or patchy zoning indicative of magmatic growth. The zircon from the enclaves is distinct from that from the host syenite in both morphology and zoning pattern, indicating that it crystallized in a different chemical environment. The contrast in zoning is particularly informative, the fine zoning in the host zircon indicating crystallization from a magma of intermediate composition, while the broad zoning in the enclave zircon is consistent with crystallization from a more mafic magma (Hoskin 2000).The partial dissolution of the AJ-17 zircon indicates that the zircon was chemically unstable at a late stage in its crystallization history, possibly because of a rise in temperature (Bora *et al*. 2013).

Twenty-four zircon grains from sample AJ-15 were analysed. The zircons have moderate to high U (305–1336 ppm) and Th (332–2840 ppm) contents, and moderate to high Th/U ratios(0.90–2.13), all consistent with crystallization from the residual melt in a mostly crystalline mafic magma. All analyses, even before common Pb correction, are concordant or nearly concordant within analytical uncertainty (Figure 7(c)). There is scatter in the radiogenic $^{206}Pb/^{238}U$, however. Omission of two high outliers and three low outliers, none of which is the analysis of a CL-dark centre, leaves 18 analyses that have the same radiogenic $^{206}Pb/^{238}U$ within analytical uncertainty, giving a weighted mean age of 90.2 ± 0.7 Ma (MSWD = 3.0). Sixteen grains from sample AJ-17 were analysed. The zircons have moderate to high U (317–1346 ppm) and Th (284–2400 ppm) contents, and moderate to high Th/U ratios (0.71–1.63), again consistent with crystallization from the residual melt in a mostly crystalline mafic magma. Even before correction for common Pb, most analysed spots are concordant within analytical uncertainty (Figure 7(d)). After omission of one high outlier (AJ-17-7.1), the remaining 15 analyses have the same radiogenic $^{206}Pb/^{238}U$ within analytical uncertainty, giving a weighted mean age of 91.6 ± 0.7 Ma (MSWD = 1.4).

The zircon ages obtained from the hybrid enclaves are, within uncertainty, the same as those from the host rocks, consistent with the host and MME-forming magmas being coeval. None of the analysed zircon cores from either rock type was significantly older than the magmatic zircon rims, suggesting that the 'cores' are in fact just an early stage of magmatic zircon growth. The few zircons older than the main age groups, on the other hand, might be residual from an earlier stage in the evolution of the magma system.

6. Discussion

6.1. Origin of MMEs

Trace element compositions of the mafic enclaves are very similar to those of the nearby mafic unit shown as Ghamishlu in Figure 1 (Figure 6(c,d)). This strongly suggests that the magma that formed the enclaves was the same magma that produced the Ghamishlu mafic intrusion. There are three main theories concerning the petrogenesis of mafic enclaves in granitic rocks: (1) they represent cognate fragments of cumulate minerals (e.g. Dahlquist 2002), (2) they are fragments of refractory restite inherited from the source rock (e.g. Chappell *et al*. 1987; Chappell and White 1991), and (3) they are blobs of hot mafic magma that intruded and were trapped in the host felsic magma, representing magma mixing (e.g. Chen *et al*. 2009; Alves *et al*. 2009). The last model, in particular, has been well documented by many studies worldwide. Our new zircon U–Pb ages obtained from the enclaves and their host rocks strongly suggest that the two interacting magmas were coeval. Field, petrographic and chemical evidence described in the present work clearly show that mechanical and chemical exchange at the contact between the two magmas might have played an important role during their mixing. In this case the cognate cumulate and restite models are unlikely to apply. The low SiO_2 (42–52 wt.%) and high MgO (3.8–6.2 wt.%) of the mafic enclaves suggest that the precursor of the enclaves was possibly an ultramafic magma. The mafic enclaves are characterized by low Ni (11–40 ppm) and Cr (10–100 ppm) relative to unfractionated primary basalts (Ni >400–500 ppm and Cr>1000 ppm; Wilson 1989), suggesting that the magma that formed the enclaves was highly evolved before interacting with the host syenitic magma. This implies that significant fractionation of olivine and pyroxene had occurred in the primary magma before the process of magma mixing.

6.2. Petrogenesis of host syenite

The numerous genetic models that have been proposed to explain the formation of syenites fall into three broad categories: (1) partial melting of crustal materials (e.g. Tchameni *et al*. 2001; Wang *et al*. 2017), (2) mixing of basaltic magma with crustal melt (e.g. Mingram *et al*. 2000; Vernikovsky *et al*. 2003; Burmakina and Tsygankov 2013) and (3) fractional crystallization of mantle-derived mafic magma, with or without crustal interaction (e.g. Mingram *et al*. 2000; Litvinovsky *et al*. 2002; Riishuus *et al*. 2005; Zhu *et al*. 2017). The lack of old inherited zircon in the investigated syenitic samples could be used as an argument against models in which ancient basement rocks played a significant role in the generation of syenite, although the extreme solubility of Zr in alkaline magmas might also be the explanation. Given the evidence assembled above, however, it is the last model that is the most applicable in the present case. This is consistent with the involvement of fractional crystallization in the petrogenesis of microgranular enclaves and

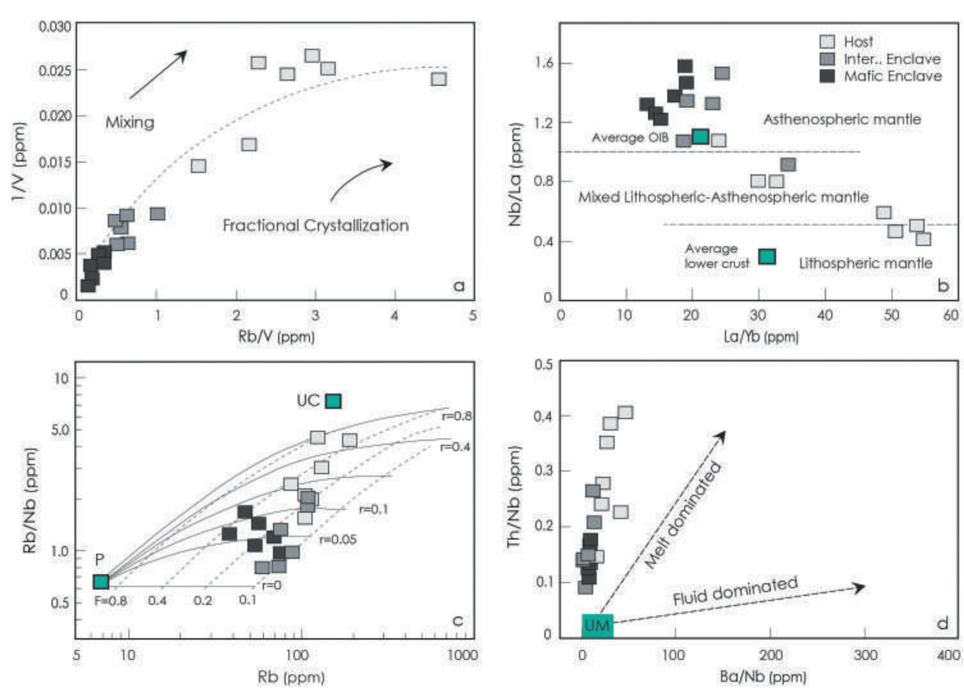

Figure 8. (a) Rb/V vs. 1/V diagram (Schiano *et al*. 2010). (b) Nb/La vs. La/Yb diagram (Abdel-Rahman and Nassar 2004). (c) Rb vs. Rb/Nb diagram (Pearce *et al*. 1990), all showing the results of assimilation-fractional crystallization (AFC) modelling. The modelling was conducted using the AFC equations of De Paolo (1981) P: parental basaltic magma compositions (Pearce *et al*. 1990), UC: composition of average upper crust (Taylor and McLennan 1985),r: ratio of assimilation to fractional crystallization, F: fractional crystallization ratio. (d) Th/Nb vs. Ba/Nb diagram (Zamboni *et al*. 2016)(UM: upper mantle).

their host (e.g. Clemens and Wall 1988; Wiebe *et al.* 1997).

The chemical signature of the Urumieh syenitic rocks indicates formation in an arc setting. Normally for continental arc granitoids, a fundamental role is assigned to mantle-derived mafic magmas (Arvin *et al.* 2007). The Mg number of the syenite (29–34) is higher than that of experimental magmas generated by partial melting of basalts (Rapp and Watson 1995), however, consistent with the syenite being generated from a mafic mantle-derived magma. The large volume of the surrounding enclave-forming mafic body relative to the syenitic unit (Figure 1) and also comparable trace element behaviour (Figure 6) indicates that the mafic intrusions could be an appropriate parent for the host magma. This argument is further supported by the curvilinear trends of major and trace elements versus silica, similar variations and enrichment of incompatible elements and identical mineralogical composition of enclaves and their host. The syenitic magma was most likely differentiated from the enclave-forming mafic magma through the fractional crystallization process; as indicated by the inverse relationship observed between Rb/V and V content (Figure 8(a)).

6.3. Crustal contamination versus source enrichment

Enrichment of the LILE and LREE, and depletion of the HFSE, in both enclaves and host, suggests that both are derived from the partial melting of an enriched source. Nb/La and Nb/Ce ratios in mantle-derived rocks are about 1.01 and 0.39 (Sun and McDonough 1989) respectively, higher than those in the continental crust (0.46 and 0.23) (Weaver and Tarney 1984). Average Nb/La and Nb/Ce ratios in the studied host rock (0.67 and 0.42), hybrid (1.34 and 0.76) and mafic (1.38 and 0.72) enclaves are significantly higher than crustal values. Furthermore, all lithologies have high average ratios of Nb/U (host 23, hybrid enclaves 34, and mafic enclaves 36) and Ce/Pb (host 67, hybrid enclaves 86, and mafic enclaves 59), much higher than those of average continental crust (Nb/U 6.2 and Ce/Pb 3.9; Rudnick and Fountain 1995). Such features cannot be explained by crustal contamination or assimilation, and most likely are inherited from enriched mantle. Furthermore, the lack of a negative Eu anomaly in all igneous facies indicates that crustal rocks in which plagioclase is stable have not played a significant role in the petrogenesis of the interacting magmas. This is consistent with previous interpretations of rocks derived by differentiation from an enriched mantle source with little or no contribution from the crust (e.g. Shellnutt *et al.* 2009).Because Ba, as an incompatible or mobile element, does not change during sediment partial melting and sediment dehydration, and Th is compatible in aqueous fluids and incompatible during sediment melting (Johonson and Plank 1999; Class *et al.* 2000), the Th/Nb ratio in a rock for a given Ba/Nb is a measure of the enrichment of the source from which it was derived. The high Th/Nb in the Urumieh rocks (Figure 8(b)) is interpreted as reflecting metasomatism of the mantle source via sediment melting, rather than by fluid fluxing. Despite the mantle source enrichment, the Rb vs. Rb/Nb plot (Figure 8(c)) shows that the host syenite may have been slightly affected by some crustal materials. Further support for this interpretation is provided by the Th/Ta ratio as a sensitive indicator of mantle-crust interaction. Mantle-derived rocks have a Th/Ta ratio of 2.1 (Sun and McDonough 1989) while the average of this ratio in the host syenite, hybrid and mafic enclaves is 5.2, 2.6 and 2.1 respectively, supporting some participation of crustal components in the genesis of the host rock, but less likely in the genesis of the enclaves.

6.4. Estimation of pressure and temperature

The Al-in-hornblende method proposed by Schmidt (1992) can be used to infer the pressure at which the magmas crystallized. The calcic amphiboles in both the host syenite and enclaves are present within the mineral assemblage Qz-Pl-Hbl-Kfs-Bt-Ttn-Mag, which is appropriate to the use of the technique. The calculated pressure ranges are 2.60–2.99 kbar (average 2.83 kbar; equivalent depth ~10.5 km) for the amphibole in the host rocks, 2.06–2.37 kbar (average 2.24 kbar; depth ~8.3 km) in the hybrid enclaves and 1.02–3.07 kbar (average 2.20 kbar; depth ~8 km) in the mafic enclaves. These results are consistent with the fractionation of felsic host syenite from the MEE-forming magma at deeper levels and subsequently their interaction at shallower levels.

Magma temperatures were calculated for the individual hornblende-plagioclase pairs (Holland and Blundy 1994) from the different samples. At the pressures calculated above, crystallization temperatures ranging from 700 to 730 ± 40°C (average 716°C) for the host syenite, 604 to 766 ± 40°C (average 676°C) for the hybrid enclaves and 525 to 758 ± 40°C (average 662°C) for the mafic enclaves were calculated. These results indicate that the mafic magma was quenched to the same temperature as the host magma when injected into the syenitic magma. Mixing between the felsic and mafic magmas took place at mid-crustal depths at relatively low temperature.

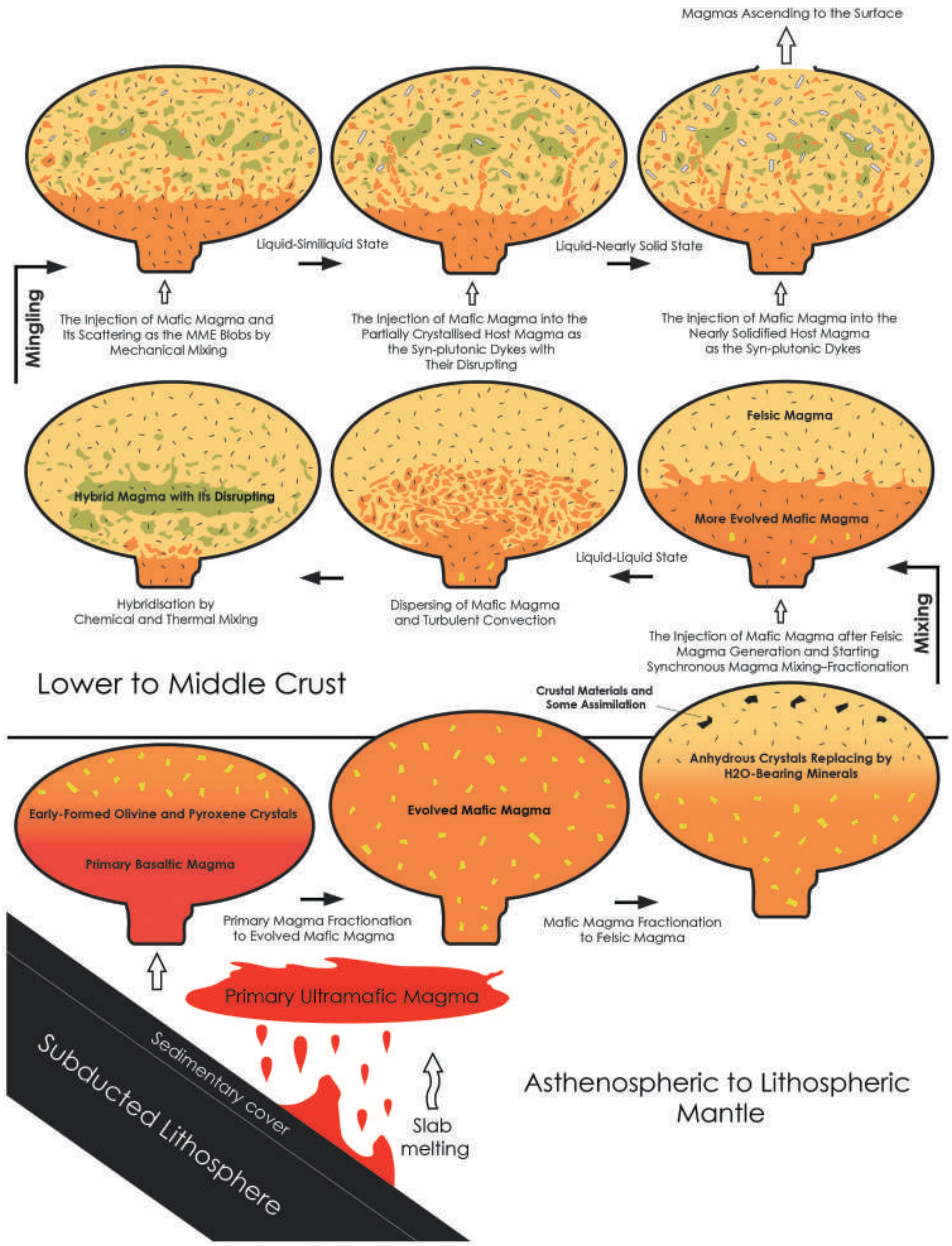

Figure 9. Schematic illustration of the sequence of processes involved in the generation, mixing and mingling of mafic and felsic magmas.

7. Magma mixing model and conclusions

The present geochemical investigation has shown that both enclave-forming magma and host syenite possibly fractionated from the same parental magma in a subduction setting. Initially, the influx of hot asthenospheric material led to bulk or partial melting of subducted sediments as well as generating a primary ultramafic magma, then an evolved mafic magma with early-formed olivine and pyroxene (Figure 9). A more felsic magma (the syenitic host) was then generated as the mafic magma evolved with magma mixing–fractionation during its ascent to mid-crustal levels. In a molten system, the coupling of mixing and fractional crystallization processes leads to simultaneous mixing-fractionation of coeval mafic and felsic magmas in a chamber during syn-crystallization with increasing polymerization and crystal loads (Zorpi *et al.* 1991; Slaby and Martin 2008; Bora *et al.* 2013; Kumar *et al.* 2017). Under such conditions anhydrous minerals in the mafic magma are destabilized and replaced by H_2

O-bearing minerals such as amphibole and biotite, possibly due to the introduction of H_2O into the primary magma, forming a fractionated mafic magma.

The presence of hybrid to mafic enclaves with syn-plutonic dikes in the host syenite probably represents various stages in the interaction between two magmas as multistage magma mixing and multiple replenishments of mafic magma. Continuous injection of mafic magma into a crystallizing felsic pluton would result progressively in a mixed hybrid component, MME and then dikes (Barbarin 2005). The injection of mafic magma into felsic raises many questions as to exactly what happens when two different types of magma are juxtaposed. Although magma mixing is a complex process and depends on many factors, it could be explained more understandably in liquid-liquid and semi-liquid-liquid and/or nearly solid-liquid states, as many intrusions show widespread evidence for juxtaposition of different magmas in different states which lead to mixing and mingling. In a plutonic setting, magma accumulation in a chamber allows it to become more or less crystallized. In such conditions, the crystallinity of the interacting magmas and thus viscosity play important roles in the mixing process.

In a liquid-liquid state or less crystallized magmas, from a general mechanical point of view, the injection of hot mafic magma into a cooler felsic magma results in cooling of the mafic magma (and possibly superheating of the felsic), so both approach similar viscosities and interact mechanically so that the hot magma is broken into smaller pieces by fragmentation processes (convection and other dispersal forces) and distributed within the cooler magma (Figure 9). Eventually thermal equilibrium is reached, allowing chemical exchange and extensive modification, leading to more complete mixing and homogenization. Overtime the magma chamber evolves progressively with the crystallization of the host. As crystal contents increase during cooling of the host magma, the viscosity increases and contrasting rates of turbulent convection diminish (Furman and Spera 1985; Turner and Campbell 1986). Once the host reaches a fully-solid state, chemical equilibration slows, then stops. The magmatic interaction changes from chemical mixing to more mechanical mixing over time, resulting in magma mingling. The mingling stage will produce distributed mafic enclaves, disrupted mafic dikes or syn-plutonic mafic dikes as the state of the host magma progresses from relatively semi-liquid to nearly solid (Figure 9). The last stage in this process was not evident in the study area, possibly because there was insufficient time for the intruded mafic magma to fill the fractures in the nearly to completely crystallized felsic host. The dispersion of the newly added mafic magma became limited due to its high thermal-rheological-viscosity contrast with the host magma (e.g. Femandez and Barbarin 1991). Accordingly, it can be concluded that mixing and mingling mostly depend on different stages of host crystallization, which strongly influence rheological differences.

Research highlights

- Enclaves and host are coeval, genetically related and evolved by synchronous magma mixing–fractionation.
- Host rocks and enclaves yields mutually indistinguishable late Cretaceous crystallization ages.
- The transition from mixing to mingling depends on the different crystalline states of the interacting magmas, especially the host magma.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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