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Magma mixing/mingling in Salmas granodiorite, NW Iran: evidence from mafic microgranular enclaves

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Abstract The interaction of mafic–intermediate and felsic rocks of the Salmas plutonic rocks produced mixed rocks (granodiorites) which contain mafic microgranular enclaves (MMEs). Enclaves ranging from a few millimeters to centimeters in size, and from ellipsoidal to rounded in shape. Based on both field observation and mineralogical compositions, MMEs are composed of quartz diorite whereas the felsic host rocks comprise mainly granodiorite. MMEs are characterized by a microporphiritic texture and revealed some types of microscopic textures, e.g., prismatic-cellular plagioclase with spike zones and rounded plagioclase megacrysts, blade-shaped biotite and acicular apatite. The host rocks show textures such as oscillatory- and reversely zoned plagioclase with spike zone. Compositions of plagioclases (An_{41} to An_{48}) of MMEs are similar to those of host rocks (An_{38} to An_{45}) which suggest partial to complete equilibration during mafic–felsic magma interactions. The individual petrographic and microstructural textures and mineral chemistry similarities between the MMEs and their host rocks and diorites indicate that the enclaves are of mixed origin and most probably formed by interaction of lower crust magma (granitic melt) and evolved mantle-derived magmas (diorites).

Keywords Magma mingling · Magma mixing · Mafic magmatic enclave (MME) · Salmas granitoides

Introduction

Mafic microgranular enclaves (MME) are common in felsic and intermediate igneous rocks which have been studied by many authors (Barbarin and Didier 1992; Elburg 1996; Silva et al. 2000; Waight et al. 2000; Perugini et al. 2003; Kumar et al. 2004). They can provide significant information on the nature of the source rocks, the mechanism of production of granitic melt, as well as evidence of interaction between continental crust and mantle. A variety of theories (magma mixing/mingling process, fragments of country rocks picked up during intrusion of the pluton and restite) have been suggested for MME and for their accumulation in igneous rocks (White and Chappell 1977; Vernon 1983; Dorais et al. 1990; Didier and Barbarin 1991b; Blundy and Sparks 1992). However, magma mixing/mingling (either as two coeval magmas or as cogenetic mafic and felsic magmas), in particular, has been well documented by many geologists as a mechanism for the genesis of MME and has been applied in studies of granites worldwide (Didier and Barbarin 1991a; Blundy and Sparks 1992; Silva et al. 2000; Barbarin 2005). Direct evidence of the interaction of mafic and felsic magmas can be seen in numerous outcrops that include mafic microgranolar enclaves, chilled and crenulated margins of the enclaves, mixed rocks and similar xenocrysts in both magmas (Wiebe et al. 1997; Kumar and Rino 2006).

Mixed rocks of the Salmas plutonic rocks in NW Iran contain numerous dark-colored enclaves ellipsoidal to rounded in shape and irregularly distributed throughout the pluton. This paper presents field observations as well as petrographical evidence and mineral chemistry of mafic microgranular enclaves and host granodiorites to investigate the petrogenesis, emplacement, and mechanism of formation of these MMEs.

Geological setting

The Salmas plutonic rocks, located about 10 km northwest of Salmas, Iran, belong to the Sanandaj-Sirjan Zone (SSZ)

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(Fig. 1). The SSZ represents the suture zone between the Afro-Arabian and the Iranian plate which is a result of the opening and later closure of the Neotethys between Eurasia and Arabia (Berberian and King 1981; Mohajjel et al. 2003; Ghasemi and Talbot 2006). The Sanandaj–Sirjan zone is characterized by deformed metamorphic rocks which are associated with numerous plutons and a widespread volcanism. The plutons cropping out in the North part of the SSZ (i.e., Qorveh, Urumieh, Alvand, Saqez, Malayer-Boroujerd) are generally formed during the Mesozoic (Torkian et al. 2008; Ghalamghash et al. 2009; Shahbazi et al. 2010; Arian et al. 2011; Deevsalar et al. 2014). Based on the timing of similar plutonic rocks in the SSZ (Ghaffari et al. 2013), emplacement of Salmas pluton could have occurred during Cretaceous. The mixed rocks (granodiorites) cover an area of approximately 20 km^2 and are exposed at the contact of granitic and mafic–intermediate stocks which all of them are emplaced into Precambrian metamorphic complex (Khodabandeh et al. 2002; Ghaffari 2008; Ghaffari et al. 2013). Marble, recrystallized limestone and a skarn zone have developed at the contact of mafic–intermediate rocks with the limestone which is a common phenomenon in North West of Iran (Mollaei et al. 2009; Mollai et al. 2014). The Quaternary basaltic rocks which occurred after Late Miocene calc-alkaline magmatism are the last phase of magmatism activity (Dabiri et al. 2011). According to field observations, the granodiorites contain mafic microgranolar enclaves (MMEs) which display magma mixing/mingling evidence.

Sampling and analytical techniques

More than 200 samples of the all rock types, granodioritic, mafic–intermediate, and felsic rocks and MMEs were collected from the Salmas pluton. After macroscopic and microscopic investigation, six samples of host rocks and MMEs were selected for Electron Microprobe analyses. Mineral analyses were conducted at Centro de Geologia da Universidade de Lisboa (CeGUL) Electron Microprobe Laboratory using a JEOL JXA-8200 electron probe microanalyzer outfitted with combined WDS and EDS systems. The analyses were conducted at an accelerating voltage of 15 kV (18 kV for opaque minerals) and a beam current of 10 nA.

Field relationships

The Salmas plutonic rocks are characterized by a variety of unites consist of felsic, mafic–intermediate, mixed rocks and mafic microgranular enclaves which display magma mixing/mingling structures (Fig. 2). The felsic intrusion is lithologicaly made up of granite on which has mixed and rarely sharp contact with the mafic–intermediate rocks. The

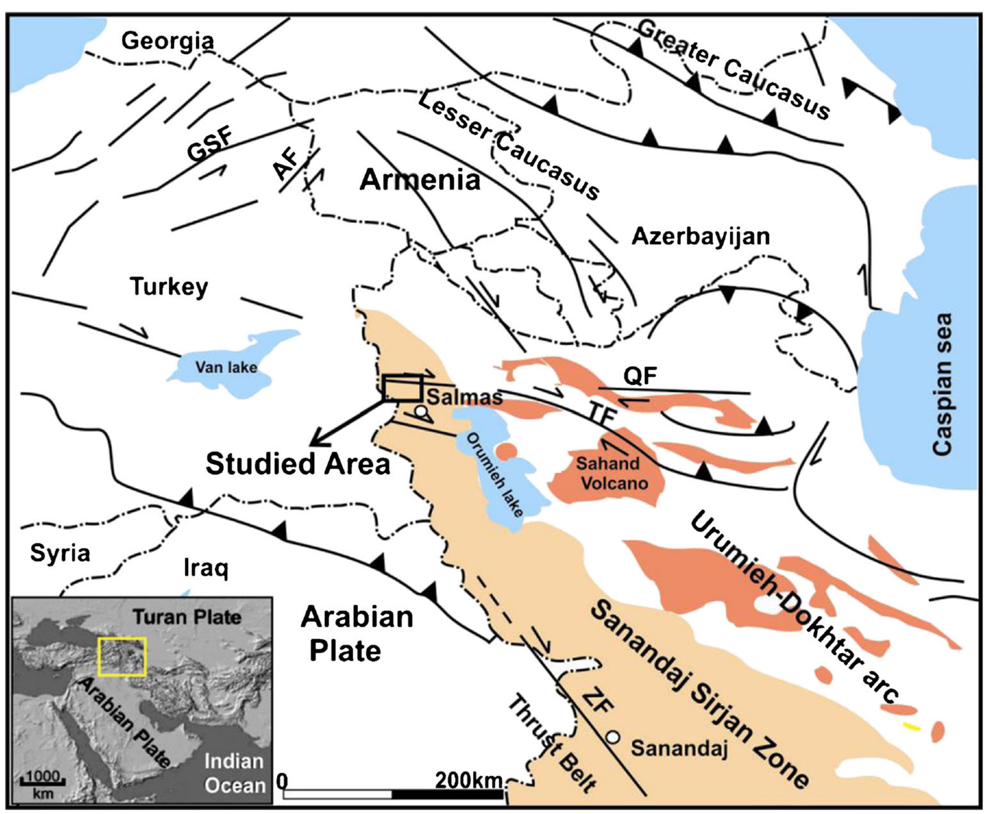

Fig. 1 General tectonic map of NW Iran and tectonic setting of the SSZ in western Iran. Several major faults are shown: Tabriz fault (*TF*), Qoshadagh fault (*QF*), Zagros fault (*ZF*)

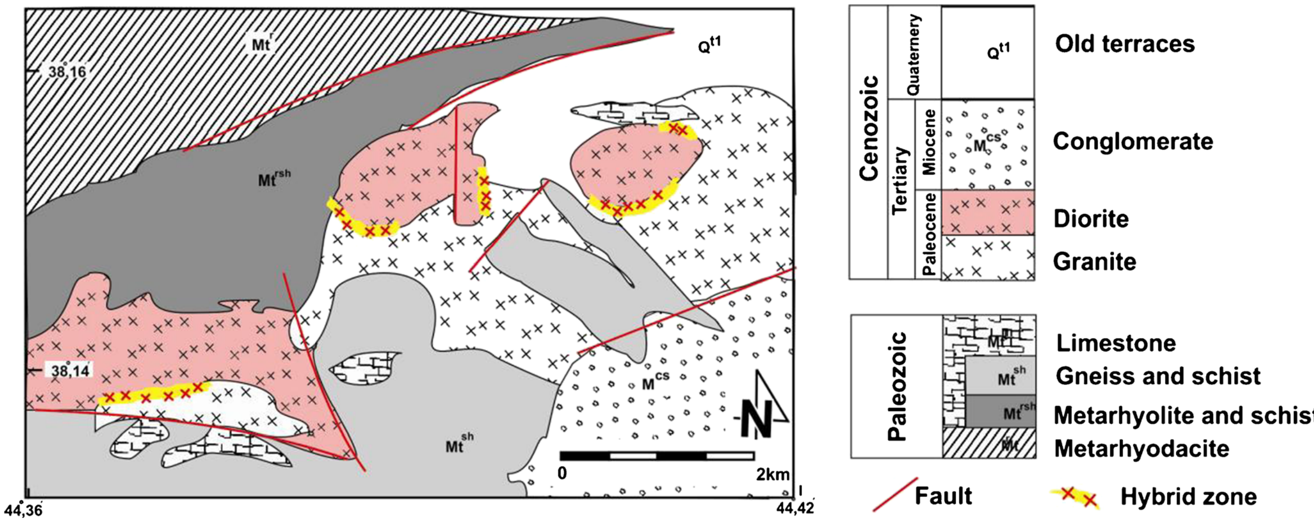

Fig. 2 Simplified geological map of the Salmas plutonic complex, showing the distribution of mixed rocks at the contact of plutons [modified after Khodabandeh et al. (2002)]

mafic–intermediate intrusion has gabbro to diorite composition which their contact with the metamorphic complex is sharp. They have fine- to coarse-grained texture and vary from dark gray to white gray in color. In the contact of mafic–intermediate and felsic rocks there, is an outcrop of mixed rocks which display compositions intermediate between felsic and dioritic rocks (Fig. 3a). The mixed rocks contain mafic microgranular enclaves which show sharp and partly diffuse contact with host rocks. MMEs are mostly 1–30 cm in diameter, typically showing spheroidal to ellipsoidal–ovoidal shape, crenulated surface, porphyritic hypidiomorphic granulare–equigranular texture, finer grain size (0.03–0.5 mm), and xenocrysts of their host (quartz and plagioclase) (Fig. 3a, b, c). In some cases, the MME have irregular chilled margins and pillow-like structures (Fig. 3d).

Petrography

The granites have a medium- to course-grained hypidiomorphic texture. The main rock-forming

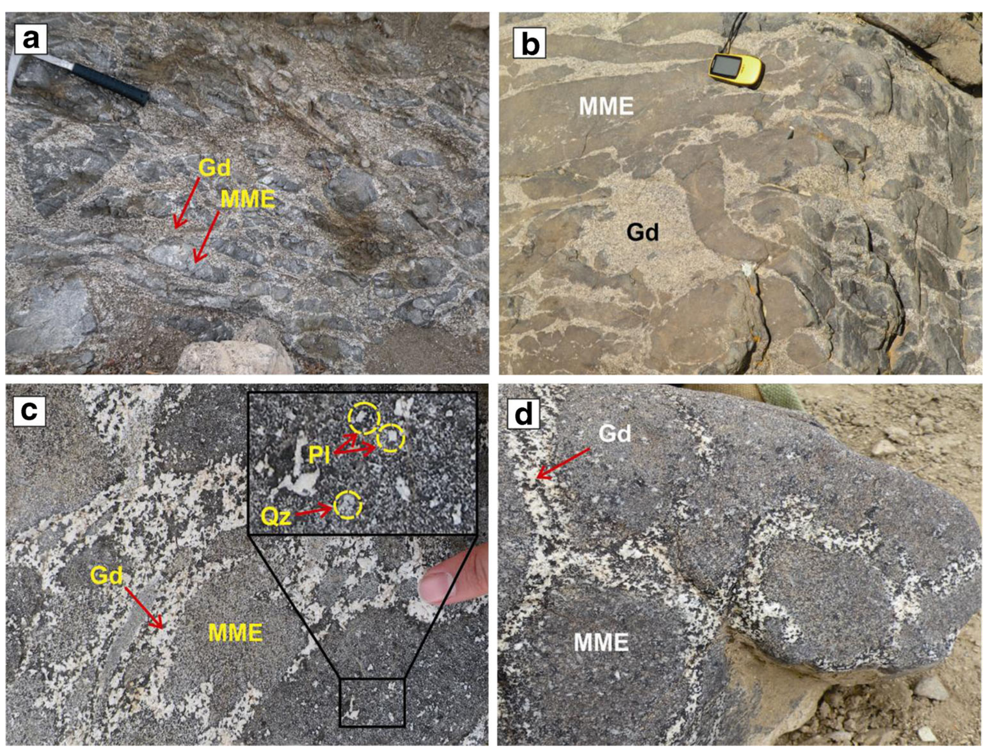

Fig. 3 Field photographs of the associated granodiorite (*Gd*)-MME. **a** Typical exposure of the granodiorite and MMEs at the contact of mafic–intermediate and felsic rocks. **b** MMEs with different size in granodioritic rocks. **c** Contact between granodiorite and mafic enclaves, the *yellow circles* highlight xenocrysts incorporated into MMEs. **d** Pillow-like enclaves in mixed rocks

minerals in granites are K-feldspar, plagioclase, quartz, and mafic minerals (biotite and hornblende). Minor/accessory minerals include apatite, zircon, subhedral titanite, and Fe–Ti oxides. The mafic–intermediate rocks consist of plagioclase, clinopyroxene (diopside to augite), ortopyroxene (hyperstene), amphibole, biotite, Fe–Ti oxides, and accessory apatite and zircon (Ghaffari et al. 2013).

The mixed rocks are composed of granodiorite which their mineral assemblages are very similar to their MMEs. They contain abundant phenocrysts of plagioclase, quartz, K-feldspar, amphibole, biotite ± pyroxene, and subordinate amounts of apatite, zircon, titanite, magnetite, and illmenite. Plagioclase mainly shows reversely zoned prismatic and lath-shaped crystals (Fig. 4a). Some plagioclase phenocrysts show oscillatory zoning with spike zones (Fig. 4b), albite twinning, cellular growth, and poikilitic textures (Fig. 4c, d). Biotite varies in form from anhedral grains to subhedral blade-shaped crystals. Needle-like crystals of apatite are mainly found in plagioclase and quartz.

The enclaves are characterized by magmatic textures, typically fine- to medium-grained with equigranular and porphyritic textures. MMEs are dioritic in composition which consists of plagioclase, amphibole, pyroxene, biotite, K-feldspar, quartz, and Fe–Ti oxides with accessory zircon and apatite. Plagioclase grains (as resorbed plagioclase phenocrysts with poikilitic textures and microlithe) show albite twining, normal, and oscillatory zoning with spike zones and spongy cellular textures which are compositionally similar to those in the host rocks (Fig. 4e). In some cases, the large plagioclase minerals cross-cut the enclave/host boundary (Fig. 4f). Biotite forms thin knife-blade crystals which usually occur in groundmass. Clots of mafic minerals and Fe–Ti oxides are also a distinctive feature of the MMEs. The clots consist predominantly of hornblende crystals intergrown with biotite and opaque minerals (Fig. 4g). They may represent concentrations of dense, early-formed phases as proposed by Reid and Hamilton (1987). Apatite is a common accessory mineral in the MMEs, occurring as acicular crystals (Fig. 4h). This morphology is indicative of mafic magma quenching which is also suggestive of a magma mixing origin (Hibbard 1991).

Mineral chemistry

Plagioclase

Representative plagioclase compositions from the diorites, mixed rocks, and MMEs are given in Table 1 and illustrated in a ternary plot of the An–Ab–Or system (Fig. 5). Comparison of the anorthite content of plagioclase between mixed rocks (An_{38} to An_{45}) and their MMEs (An_{41} to An_{48}) reveals that the compositional ranges of enclaves and their host rocks overlap each others. Regarding a comparison between the MMEs and the host mixed rocks, it appears that not only that the rims of host plagioclases (An_{30} to An_{39}) show similarity to the rims of the MME plagioclase (An_{35} to An_{43}), but also that the cores of some of the host plagioclases (An_{47} and An_{52}) are almost identical to those observed in the cores of MME plagioclases (An_{48} to An_{53}). This similarity suggests that the plagioclase rims of the MMEs and their host rocks crystallized from a similar magma which provides a further indication of a magma mixing/mingling process in the generation of the mixed rocks. The enclave plagioclase and core compositions of the zoned plagioclase in them overlap with the composition of the plagioclase in dioritic rocks (An_{44}–An_{50}). These compositional similarities of the plagioclases suggest that the enclaves are derived from dioritic magma and crystallized within the felsic magma which produced the mixed rocks.

Amphibole

According to the classification of Leake et al. (1997), the amphiboles from the diorites, MMEs and their host rocks belong to the calcic group with a chemical composition of magnesio-hornblende (Table 2; Fig. 6a, b). Studies by Schmidt (1992) have been suggested that the Al content of calcic amphibole allowed evaluating the pressure attending to pluton crystallization. Pressure calculations for amphibole compositions are given in Table 2. All data for MMEs and mixed rocks fall in the range between 2.39 and 3.15 Kbar, whereas the diorites formed under relatively high-pressure condition (2.72–4.15 Kbar).

The hornblendes of the Salmas granodiorite and its MME overlap with one another on plots of Mg/(Mg + Fe^{+2} + Mn) versus Si per formula unit (Fig. 6c). The compositional overlap between the hornblendes of MME and granodiorite indicates that the hornblendes of the MME and those of the Salmas granodiorite equilibrated during the course of their crystallization (Dorais et al. 1990).

Pyroxene

Representative pyroxene compositions from the analyzed diorites and MMEs are given in Table 3 and graphically shown in Fig. 7. According to quadrilateral diagram from Morimoto (1988), the analyzed crystals of clinopyroxene and orthopyroxene in all samples have the same narrow compositional range (Fig. 7) in the diopsid-augite ($Wo_2En_{57-72}Fs_{26-41}$) and hypersthene ($Wo_{42-46}En_{36-42}Fs_{12-21}$) field, respectively. Two pyroxenes

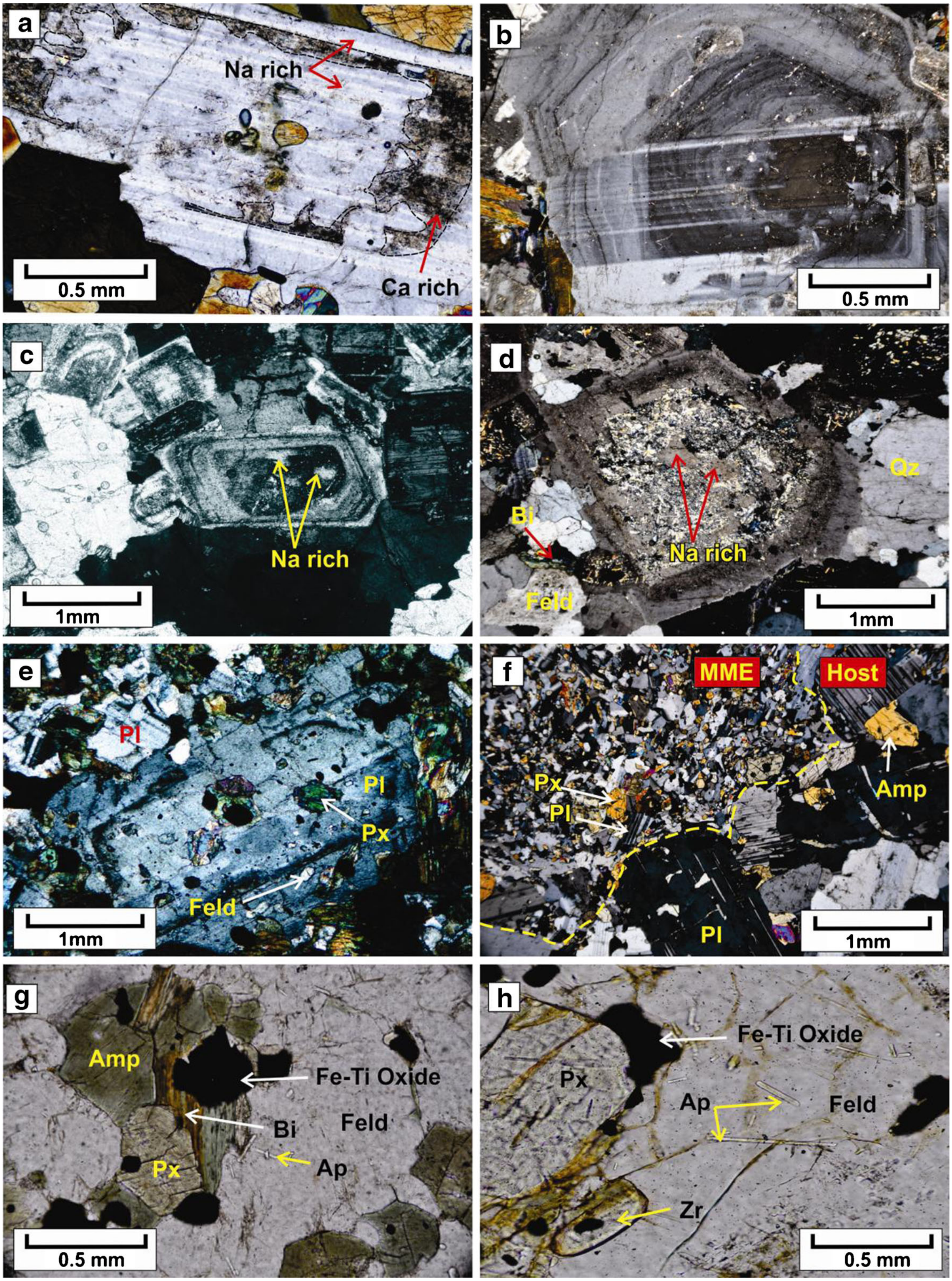

Fig. 4 Microphotographs showing certain textural features of the host granodiorites and their enclaves: **a** reverse zoning in plagioclase of host rock; **b** oscillatory zoning in plagioclase phenocryst of host rock; **c**, **d** cellular plagioclase phenocryst with spike zone in host rock; **e** poikilitic texture in a large plagioclase xenocryst hosted in MME with resorbed rims; **f** large plagioclase cross-cutting the enclave/host boundary; **g** clots of mafic and opaque minerals in MMEs; **h** apatite needles and zircon minerals in MME

geothermometery using the calibration of Lindsley (1983) resulted in temperatures between 700 to 1,000 °C for the hypersthene-bearing assemblages and 550 to 800 °C for diopside-augite assemblages.

Table 1 Representative analyses of plagioclase of the Salmas plutonic rocks

Rock	Diorite				MME					
Sample	P318		P303		P307b					
Position					R	C	R	C	M	M
SiO_2	57.11	56.39	56.91	54.16	58.73	54.79	57.34	55.63	56.37	55.99
Al_2O_3	26.94	26.92	27.01	29.30	25.02	28.47	26.73	27.86	27.20	27.24
FeO	0.20	0.28	0.19	0.26		0.17		0.24	0.15	0.19
CaO	9.16	9.42	9.48	10.09	7.34	10.94	9.14	9.92	9.50	9.85
Na_2O	6.07	5.89	5.95	5.37	7.26	5.37	6.31	5.84	6.01	5.66
K_2O	0.28	0.26	0.29	0.04	0.32	0.08	0.23	0.06	0.24	0.22
Total	99.8	99.2	99.8	99.22	98.7	99.8	99.8	99.6	99.5	99.2
An %	44.7	46.2	46.0	50.8	35.2	52.7	43.9	48.2	46.0	48.4
Ab %	53.6	52.3	52.3	48.9	63.0	46.8	54.8	51.4	52.6	50.3
Or %	1.7	1.5	1.6	0.2	1.8	0.4	1.3	0.3	1.4	1.3

Rock	MME										Mixed rocks	
Sample	P371										P307a	
Position	R	C	R	C	R	C	M	M	M	M	R	C
SiO_2	59.32	54.75	59.09	55.62	58.18	54.99	56.49	56.87	57.73	56.55	61.32	55.18
Al_2O_3	25.93	28.39	25.22	27.78	26.34	28.37	27.34	27.26	26.94	26.34	25.18	28.01
FeO		0.32		0.16	0.14	0.25	0.23	0.21	0.15	0.30	0.02	0.29
CaO	6.85	10.69	7.85	10.47	8.43	10.77	9.76	9.38	8.88	8.70	6.27	10.38
Na_2O	6.48	5.57	7.69	5.58	7.11	5.48	5.77	6.12	6.42	6.51	8.04	5.52
K_2O	0.36	0.08	0.23	0.12	0.12	0.07	0.26	0.21	0.21	0.44	0.10	0.07
Total	98.9	99.8	100.1	99.7	100.3	99.9	99.8	100.0	100.3	98.8	100.9	99.4
An %	36.0	51.2	35.6	50.5	39.3	51.9	47.6	45.3	42.8	41.4	29.9	50.7
Ab %	61.7	48.3	63.1	48.8	60.0	47.7	50.9	53.5	56.0	56.1	69.5	48.9
Or %	2.3	0.4	1.2	0.7	0.7	0.4	1.5	1.2	1.2	2.5	0.6	0.4

Rock	Mixed rocks											
Sample	P307a					P396						
Position	R	C	M	M	M	R	C	C	R	M	M	M
SiO_2	58.18	55.31	57.06	59.10	57.55	59.78	55.58	56.82	61.03	57.52	57.96	57.18
Al_2O_3	26.34	28.14	27.03	25.67	26.78	25.63	27.95	27.75	25.16	27.01	26.38	26.87
FeO	0.14		0.13	0.19	0.18	0.03	0.17	0.47		0.31	0.19	0.31
CaO	8.43	10.86	9.18	7.71	8.80	6.83	10.09	9.84	7.43	9.03	8.41	9.02
Na_2O	7.11	5.48	6.05	6.45	6.28	7.56	5.51	5.68	7.18	6.36	6.69	6.12
K_2O	0.12	0.12	0.23	0.77	0.27	0.42	0.28	0.49	0.53	0.32	0.27	0.24
Total	100.3	99.9	99.7	99.9	99.9	100.3	99.6	101.1	101.3	100.5	99.9	99.7
An %	39.3	51.9	45.0	38.0	42.9	32.5	49.5	47.5	35.3	43.2	40.4	44.3
Ab %	60.0	47.4	53.6	57.5	55.5	65.1	48.9	49.7	61.7	55.0	58.1	54.3
Or %	0.7	0.7	1.4	4.5	1.6	2.4	1.6	2.8	3.0	1.8	1.5	1.4

Ab albite, *An* anorthite, *Or* orthoclase., *C* core, *R* rim, *M* matrix

Discussion

Evidence for magma mixing/mingling

Existence of MMEs in the host granodioritic rocks indicates that two melts with different composition interacted during the generation of Salmas plutonic rocks. The MMEs are not cognate fragments of cumulate minerals or refractory “restite” from source-rock anatexis. They show magmatic textures such as poikilitic–equigranular to microporphiritic which are identical of basic igneous rocks. In addition, MMEs do not have any cumulate textures. Therefore, it can be concluded that at least two separate magmas are involved in their generation and restite and cumulate origins can be rejected. The

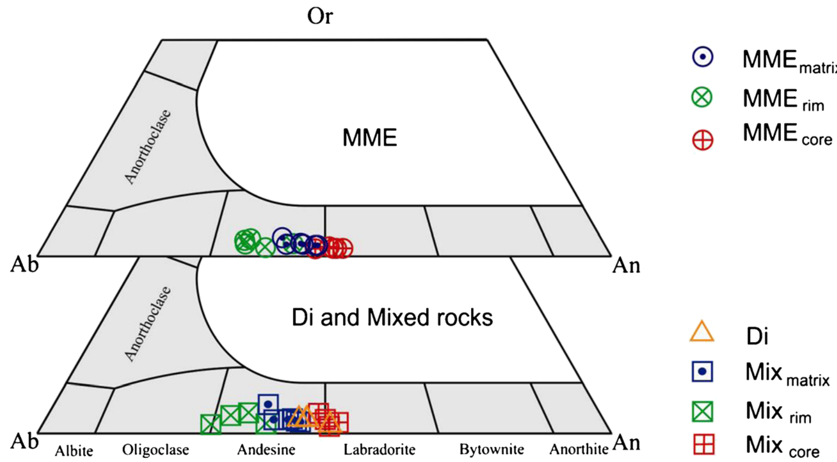

Fig. 5 Nomenclature of the plagioclases from MME, mixed rocks (granodiorites), and diorites. Core, rim, and matrix compositions are shown separately

Table 2 Representative analyses of amphibole of the Salmas plutonic rocks

Rock sample	Diorite					MME			Mixed rocks	
	P318		P303			P307b			P307a	
SiO_2	45.76	47.36	46.40	46.54	47.42	47.06	47.13	47.25	47.24	48.46
TiO_2	1.85	1.42	1.73	1.80	1.07	1.10	1.30	1.21	1.34	0.98
Al_2O_3	8.81	7.71	8.35	8.32	6.96	7.39	7.53	7.39	7.57	6.66
FeO	14.19	13.90	14.30	14.35	12.77	17.21	16.50	16.57	16.82	16.68
MnO	0.35	0.33	0.31	0.30	0.36	0.34	0.37	0.34	0.47	0.27
MgO	13.44	14.01	13.54	13.43	14.12	12.12	12.34	12.29	12.03	12.53
CaO	11.2	11.1	11.1	11.0	10.5	11.0	11.1	11.1	10.9	11.3
Na_2O	1.4	1.2	1.4	1.4	1.2	0.9	1.0	1.0	1.1	0.6
K_2O	0.4	0.3	0.4	0.4	0.3	0.5	0.5	0.5	0.5	0.5
Cr_2O_3	0.1	0.1	0.1	0.1	0.1		0.1	0.1	0.1	
Total	97.5	97.4	97.6	97.7	94.8	97.7	97.8	97.7	98.0	98.1
Structural formulae										
Si	6.6	6.8	6.7	6.7	7.0	6.8	6.8	6.9	6.9	7.0
Al iv	1.4	1.2	1.3	1.3	1.0	1.2	1.2	1.1	1.1	1.0
Al vi	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Ti	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Cr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fe^{+3}	0.9	0.9	0.9	0.9	0.9	1.0	0.9	0.9	0.9	0.9
Fe^{+2}	0.8	0.7	0.8	0.9	0.6	1.1	1.1	1.1	1.1	1.1
Mn	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Mg	2.9	3.0	2.9	2.9	3.1	2.6	2.7	2.7	2.6	2.7
Ca	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Na	0.4	0.3	0.4	0.4	0.3	0.2	0.3	0.3	0.3	0.2
K	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
(Ca+Na) (B)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9
Na (B)	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.2
(Na+K) (A)	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
$Mg/(Mg+Fe^2)$	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7
$Fe^3/(Fe^3+Alvi)$	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9
P (Kbar)	4.15	3.21	3.76	3.73	2.72	3.02	3.12	3.02	3.15	2.39

Formula based on 23 oxygens; barometry based on Schmidt (1992)

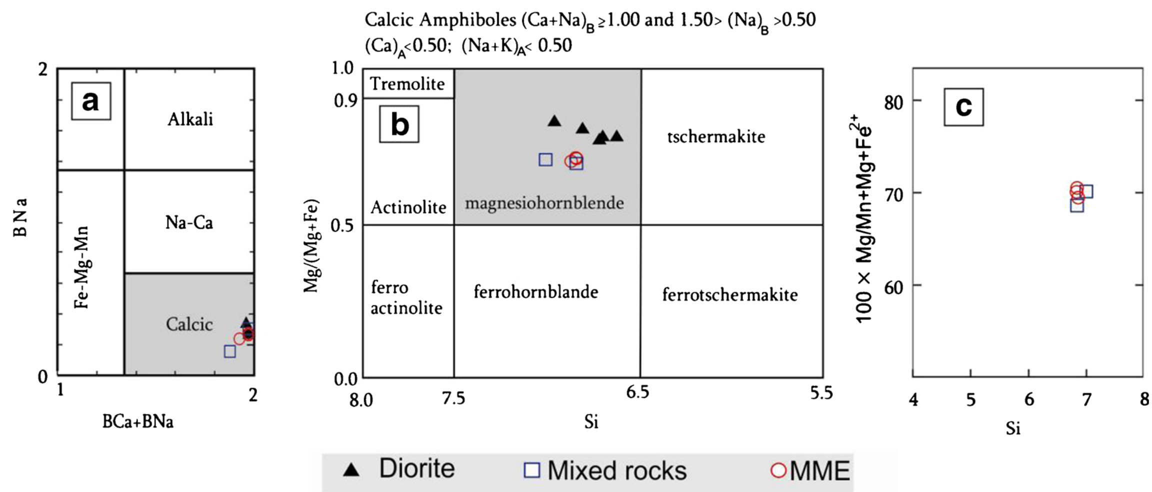

Fig. 6 **a**, **b** Classification of amphiboles from MMEs, granodiorites and diorites showing magnesio-hornblende composition (Leake et al. 1997); **c** Mg/Mg+Mn+Fe vs. Si binary diagram for amphiboles in MMEs and their host rocks

interaction process is supported by field observation, petrographic and mineral chemistry studies. The mode of occurrence of MME in granodiorites, with ellipsoidal to rounded shape, sharp but partly diffuse contact and crenulated surface have been used as evidence that MMEs were quenched globules formed from mafic magma by magma mixing/mingling processes (Hibbard 1981) (Fig. 3). Pillow-like enclaves are suggestive of the enclaves forming as mafic magma blobs being injected into the granitic host magma and undergoing quenching against the cooler felsic host (Dorais et al. 1990; Blundy and Sparks 1992; Bonin 2004) (Fig. 3d). The lack of chilled margins in MMEs indicates that enclave-forming and host magmas had a small temperature differences (Troll et al. 2004). Abundant quartz and plagioclase xenocrysts in MMEs were mechanically transferred to the mafic magma globules during the mixing process (Fig. 3c). The xenocrysts of quartz is suggested as representing a classical magma-hybridization characteristic (Vernon 1990; Hibbard 1991). It strongly advocates the disequilibrium state after mechanical transfer of crystals from felsic magma to MMEs (Hibbard 1981; Barbarin 1990b; Hibbard 1991). Mafic enclaves have textures, modes, and mineralogy similar to those of the diotitic rocks suggesting that they are genetically related. Oscillatory-zoned plagioclases, rounded plagioclase phenocryst with poikilitic textures, irregular changes plagioclase composition and its prismatic-cellular growth, blade biotite, acicular apatite in MMEs possibly record the mixing/mingling of coexisting mafic and felsic magmas (Hibbard 1981; Hibbard 1991; Janousek et al. 2000; Baxter and Feely 2002) (Fig. 4). Cellular plagioclase growth and similarity of plagioclase composition

Table 3 Representative analyses of pyroxene of the Salmas plutonic rocks

Rock sample	Diorite					MME				Mixed rocks			
	P318			P303		P307b				P307a			
SiO_2	52.98	53.49		51.66	50.07	53.37	52.87	51.20	51.61	50.58	50.41	51.07	50.92
TiO_2	0.27	0.25		0.47	0.00	0.22	0.26	0.16	0.00	1.40	0.06	0.18	0.29
Al_2O_3	2.02	1.45		2.14	1.39	1.62	2.25	1.38	1.18	0.67	0.60	1.42	1.05
FeO	17.13	17.01		7.37	9.21	17.07	17.22	10.98	10.89	25.37	24.70	12.10	13.05
MnO	0.54	0.57		0.27	0.71	0.56	0.60	0.63	0.19	0.72	0.68	0.52	0.49
MgO	25.61	25.86		14.78	13.57	25.99	25.34	15.09	14.29	19.16	19.22	12.29	12.66
CaO	0.9	1.2		22.1	22.2	0.9	1.0	21.3	22.0	1.0	0.8	21.4	20.2
Na_2O	0.0	0.0		0.3	0.3	0.0	0.0	0.4	0.3	0.0	0.0	0.2	0.3
Total	99.5	99.8	0.0	99.1	97.5	99.7	99.5	101.1	100.4	98.9	96.5	99.2	98.9
Wo %	1.9	2.3		45.6	46.0	1.8	2.0	41.9	43.6	2.1	1.7	44.7	42.0
En %	71.4	71.4		42.5	39.1	71.8	71.0	41.3	39.5	56.1	57.1	35.7	36.7
Fs %	26.8	26.3		11.9	14.9	26.4	27.0	16.8	16.9	41.7	41.2	19.7	21.2

Abbreviations: *Wo* wollastonite, *En* enstatite, *Fs* ferrosilite

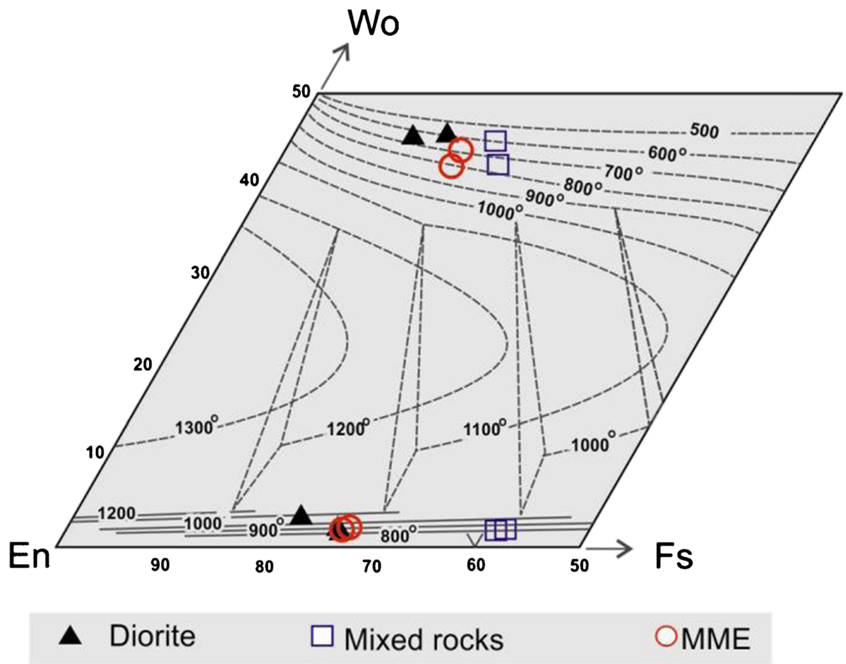

Fig. 7 Wo-En-Fs classification diagram for pyroxene in diorites, MMEs and mixed rocks (nomenclature from Morimoto (1988)). Isotherms modified from Lindsley (1983) to P=1 kbar

in host mixed rocks and their MMEs imply a mechanical transfer from host magma to enclave magma during mixing/mingling of mafic and felsic magmas (Silva et al. 2000). Low rheological contrast between mafic and felsic magmas allows crystal transfer from the host granodioritic magma into the mafic magma (Barbarin and Didier 1992; Perugini et al. 2003). Plagioclase phenocrysts with poikilitic texture and partially resorbed rims and cross-cutting the enclave/host boundary by large plagioclases is considered to prove that the enclaves were in liquid state when they were incorporated into the more felsic magma (Perugini et al. 2003) (Fig. 4e, f). Acicular shape of apatite in the MMEs, a common texture reflecting magma mixing (Hibbard 1981), indicates rapid growth in an overcooled mafic magma (Wyllie et al. 1962) (Fig. 4h).

The mixed rocks display cellular and zoned plagioclase crystals (Fig. 4a–c), inclusion of mafic phases in plagioclase, acicular apatite morphologies, blade-shaped biotites, and quartz xenocrysts, all suggest magma mixing processes (Hibbard 1981; Barbarin 1990a; Castro 2001). Abrupt decrease of anorthite contents of plagioclase from core to rim in host rocks ($An_{47–52}$ to $An_{30–39}$) (Table 1, Fig. 5), indicates that the calcic cores having crystallized from a mafic magma, were later injected into a high-level felsic magma chamber.

Proposed magma mixing model

A vast literature deals with interaction between mafic and silicic magmas. It is accepted that magma mixing or mingling

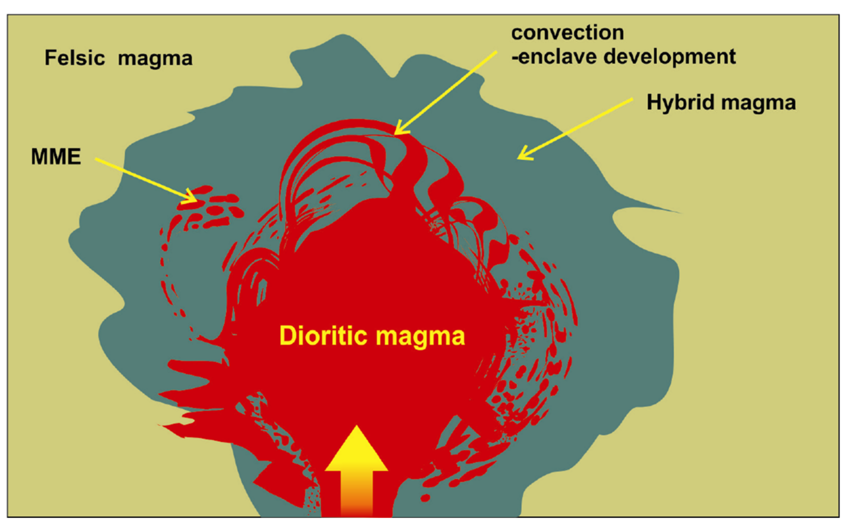

Fig. 8 Cartoon illustrating the mafic–felsic magmas interaction within the Salmas pluton magma chamber

is an important process (Neves and Vauchez 1995), which may occur in different environments such as plutonic (Hibbard 1991), volcanic, and subvolcanic (Castro et al. 1990) and in various tectonic settings such as continental arcs (Zorpi et al. 1989), island arcs (Asmerom et al. 1991), back arc basins (Barnes et al. 1995), or ocean spreading ridges (Rhodes et al. 1979). In all these environments or tectonic settings, the interaction of two different magmas is preserved in a range of ways. Donoghue et al. (1995) has proposed several scenarios for two contrasting magmas interaction: (1) one melt may freeze (quench) against the juxtaposed melt, forming net-vein complex or an acidic–basic pillow and abruptly arresting the mixing process, (2) the melts may mix physically, thereby forming a hybrid melt, (3) the two magmas may mix partially but incompletely, particularly where the two end member components are porphyritic, leaving phenocrysts from both magmas with strong disequilibrium textures; and (4) the melts may intermingle but not mix, forming a 'banded' or 'streaky' rock. The only evidence for the mixing, where process has been efficient, may be disequilibrium textures in phenocryst phases and/or linear trends in Harker variation diagrams. However, where mixing is incomplete or limited (mingling), the development of mafic microgranular enclaves or banded rocks may occur, which could retain the identity of the end-members.

The field, petrographic and mineral chemistry relations that we have documented here can be integrated in a tectonomagmatic model to construct the evolution of the Salmas granitoid and MMEs as outlined below.

As mentioned above, the similarity of textures, modes, and mineralogy between MMEs and the diotitic rocks suggest that they are genetically related. Ghaffari et al. (2013) show that the diorites are evolved via crystal fractionation of mafic magmas (gabbroic rocks) which are products of melting of spinel-peridotite source. The produced dioritic melts underplate the crust-mantle boundary. This would yield the necessary heat for the dehydration melting of the lower crust (Rushmer 1991; Rapp and Watson 1995; Petford and Gallagher 2001) and producing a granitic magma chamber (Marsh 1984; Holden et al. 1987; Huppert and Sparks 1988). The dioritic magma (as the mafic end-member) rises episodically and injects into the base of the felsic magma chamber (as the felsic end-member) which will start convection in the felsic chamber because of the mafic heat source below. Interaction between the crustal-derived and dioritic melts to varying degrees could have produced hybrid magmas (granodioritic magma) at depth. New dioritic magma pulses injection invaded the felsic magma chamber, forming MMEs, which were dispersed throughout the mixed magma by convection (Fig. 8).

Conclusions

Granodioritic rocks occur at the contact of the Salmas mafic–intermediate and felsic rocks. They contain mafic microgranolar enclaves with quartz dioritic composition and ellipsoidal to rounded shape. Field, petrographic and mineral chemistry features of MMEs in granodiotites indicate mixing/mingling of coeval mafic and felsic magmas. The MMEs are finer-grained and rich in plagioclase and hornblende than their host granodiorite. Their mineralogical association is similar to that of host and dioritic rocks. Furthermore, oscillatory-zoned plagioclases, irregular changes of anorthite contents within plagioclase, resorbed plagioclase megacrysts with poikilitic textures, blade-shaped biotite, acicular apatite, spike zones in plagioclase, prismatic-cellular plagioclase in mafic microgranular enclaves possibly record the mixing of coexisting mafic and felsic magmas. Compositional variations of plagioclase and amphibole in MMEs and host rocks are more or less similar. These feature most likely evolved by re-equilibrating during magma mixing and mingling events.

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