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PLAGIOCLASE HOSTED MELT INCLUSION IN HYPABYSSAL ROCKS IN TORUD-AHMAD ABAD MAGMATIC BELT

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Abstract

This study investigates for the first time melt inclusions (MI) that are found within fundamental minerals of subvolcanic rocks in Torud-Ahmad Abad magmatic belt. The Torud-Ahmad Abad magmatic belt is situated in south-southeast of Shahrood and belongs to the northern part of central Iran structural zone. Melt inclusions represent liquids that were trapped along growth zones (primary) or healed fractures of mineral phases, which crystallized from the silicate liquid as it cooled. Based on SEM analysis of these melt inclusions, their compositions are dacite, andesite and basaltic andesite. Thus, with the use of melt inclusions in the volcanic rocks of Torud-Ahmad Abad magmatic belt, we attempt to show the compositional evolution and origin of magma. The effective factors on magma evolution are magma mixing, fractional crystallization and crustal contamination.

Keywords: *melt inclusions; hypabyssal rocks; magma evolution; Torud-Ahmad Abad magmatic belt*

Περίληψη

Σε αυτή την εργασία, εξετάζονται για πρώτη φορά, τα εγκλείσματα τήγματος (melt inclusions - MI) που φιλοξενούνται μέσα στα ορυκτά συστατικά των υποηφαιστειακών πετρωμάτων της μαγματικής ζώνης Torud-Ahmad Abad, νότια-νοτιοανατολικά του Shahrood (στο βόρειο τμήμα της τεκτονικής ενότητας του κεντρικού Ιράν). Τα *εγκλείσματα τήγματος αντιπροσωπεύουν ρευστά που εγκλωβίστηκαν κατά τη διάρκεια της ανάπτυξης των ζωνών (πρωτογενής) ή κατά την επούλωση ρωγμών των ορυκτών φάσεων, οι οποίες κρυσταλλώθηκαν από ένα πυριτικό τήγμα κατά τη διάρκεια της ψύξης. Αυτά τα εγκλείσματα τήγματος, με βάση τις αναλύσεις SEM, αντιστοιχούν σε σύσταση δακίτη, ανδεσίτη και βασαλτικού ανδεσίτη. Έτσι, με την χρήση των εγκλεισμάτων τήγματος των ηφαιστειακών πετρωμάτων της μαγματικής ζώνης Torud-Ahmad Abad, φαίνεται η εξέλιξη και η προέλευση του μάγματος. Οι παράγοντες που συνέβαλαν στην εξέλιξη αυτών των μαγμάτων είναι η μίξη μαγμάτων, η κλασματική κρυστάλλωση και η μόλυνση από τον φλοιό.*

Λέξεις κλειδιά: *εγκλείσματα τήγματος, υποηφαιστειακά πετρώματα, εξέλιξη μάγματος, μαγματική ζώνη Torud-Ahmad Abad.*

1. INTRODUCTION

Based on previous studies, the composition of the hypabyssal rocks in Torud- Ahmad Abad are andesite, dacite and basaltic andesite (Yousefi et al., 2017a). The mineral assemblages and the composition of minerals in magmatic rocks are related to the composition and evolving conditions of the melt during crystallization (Yousefi et al., 2017b). In these rocks, accumulated ferromagnesian minerals, especially hornblende and pyroxene, occur in the form of enclaves and micro-enclaves (mafic clots). The mafic clots also include fragments of crystallized magma, formed in the earlier stages of crystallization, which were transported along with the molten magma to the upper and final magma chambers near the surface. Magma mixing and fractional crystallization processes (AFC) controlled the evolution of the magmas in Torud-Ahmad Abad magmatic belt (Yousefi et al., 2017a). The existence of enclaves of different origin suggests a process of contamination and magma mixing with continental crust. Magma mixing is a fundamental and effective process in the evolution of Iranian intermediate-silicic volcanic rocks (Rahmati Ilkhchi et al., 2006). Neave et al. (2017) believe that mantle melts are modified by a range of mixing, fractionation and assimilation processes as they rise towards the surface. Based on Cesare et al. (2015), MI (melt Inclusion) are droplets of silicate melt that are trapped in minerals during their growth in a magma. However, inclusions from each type of host mineral have distinct evolutionary trends most consistent with being mainly introduced by post-emplacement crystallization of the enclosing host, which is also supported by the composition of groundmass glasses (Streck and Wacaster, 2006). According to Neave et al. (2017), melt inclusions are formed during the early stages of magmatic evolution, trap primitive melt compositions and enable the volatile contents of primary melts and the mantle to be estimated. In this study, we discuss the origin of MI in these mineral hosts during the magma crystallization. The crystallization of MI in magmatic rocks does not relate to pressure. They may have formed at shallow crustal conditions or at mantle depths.

2. GEOLOGICAL SETTING

The Torud-Ahmad Abad magmatic belt is located in the south-south east of Shahrood, in the northern part of central Iran structural zone (East of Semnan Province, NE Iran) (Fig. 1).

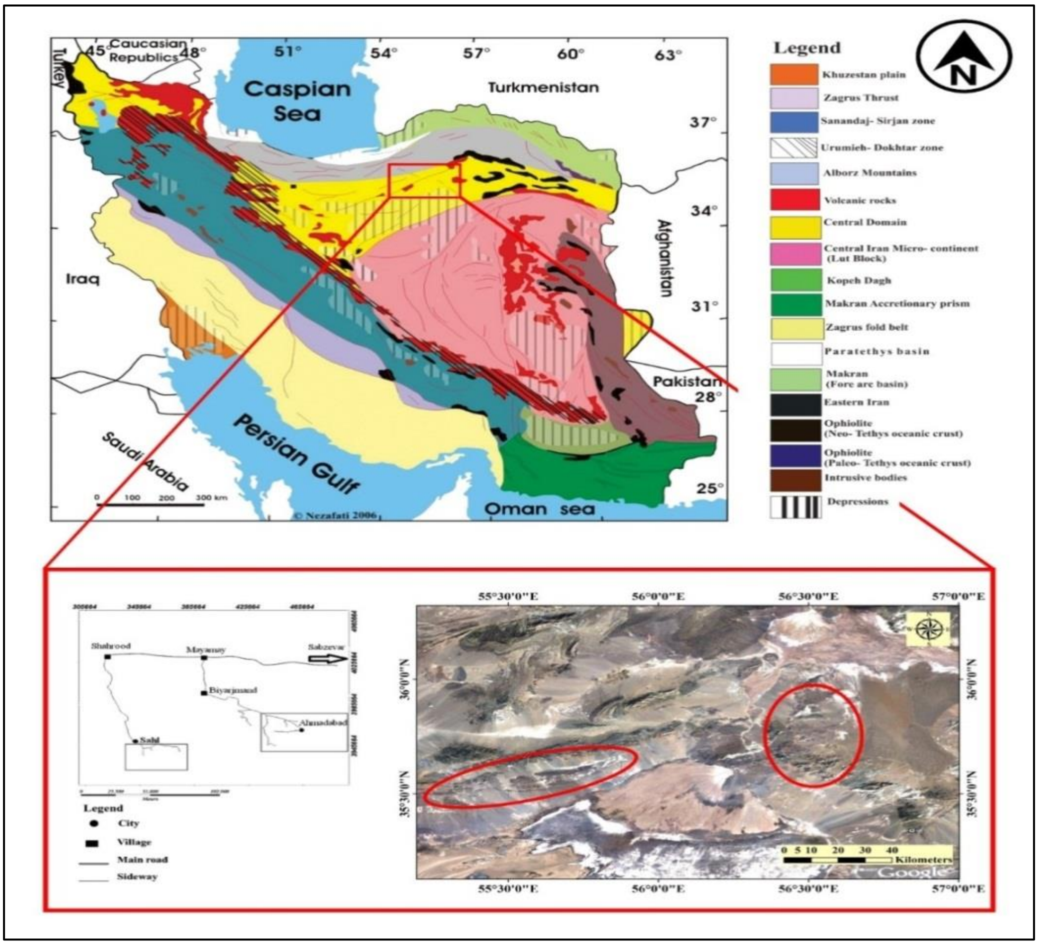


Figure 1: Distribution of middle and late Eocene hypabyssal rocks of TAMB (Torud-Ahmad Abad Magmatic Belt) in the south and south east of Shahrood (the northern part of central Iran structural zone).

The late Mesozoic northward motion of the Arabian plate towards Eurasia at a rate of 26±2mmyr^{-1} at ~59^{0}E is associated with the subduction of the Neo-Tethyan ocean under the central Iranian Plateau, which has resulted in various types of deformation in different parts of the collision zone (Jamshidi et al., 2015; Motaghi et al., 2012; Shabanian et al., 2012). During the Mesozoic and Cenozoic, central Iran was a tectonically dynamic region. In addition to several well-defined deformational events, magmatic activity can be traced in the form of volcanic and subvolcanic rocks (Fig. 2 and 3). Based on geological maps and field studies, late Neoproterozoic Mica-schist, paragneiss, amphibolite and mylonitized granites have been detected as the oldest rocks occurring in the study area. Thick sequence of Paleocene to middle Eocene volcanic and volcano-sedimentary rocks crop out in the region. This sequence was intruded by numerous dikes, hypabyssal igneous domes and one small gabbrodioritic body, with compositions ranging from trachybasaltic andesite, trachyandesite, dacite, trachyte, gabbro and diorite.

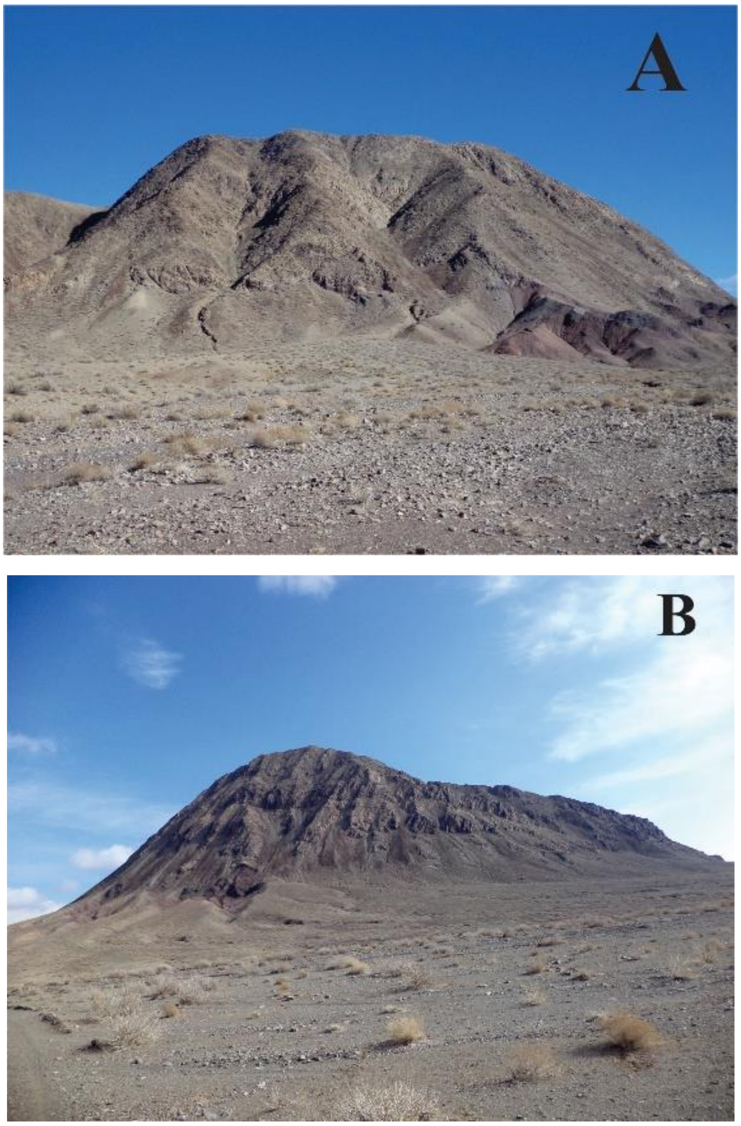


Figure 2: Two intrusions of hypabyssal rocks (Adakite rock) a) Allah Kom dacitic dome b) Bazmin andesitic dome.

3. ANALYTICAL METHODS

Three samples of andesitic, dacitic and basaltic andesitic rocks were selected for analysis of composition of melt inclusion. The chemical composition of these melt inclusions is determined by the Scanning Electron Microscope Laboratory, using a SEM (JEOL JSM-840A) equipped with an energy dispersive spectrometer (EDS, Oxford INCA 250) at Aristotle University of Thessaloniki. The analytical setting was 20 kV accelerating voltage with a 0.4 mA probe current. A pure Co standard was used for calibrating the EDS analysis. For SEM observations, the samples were coated with carbon, with an average thickness of 200 Å, using a vacuum evaporator JEOL-4X.

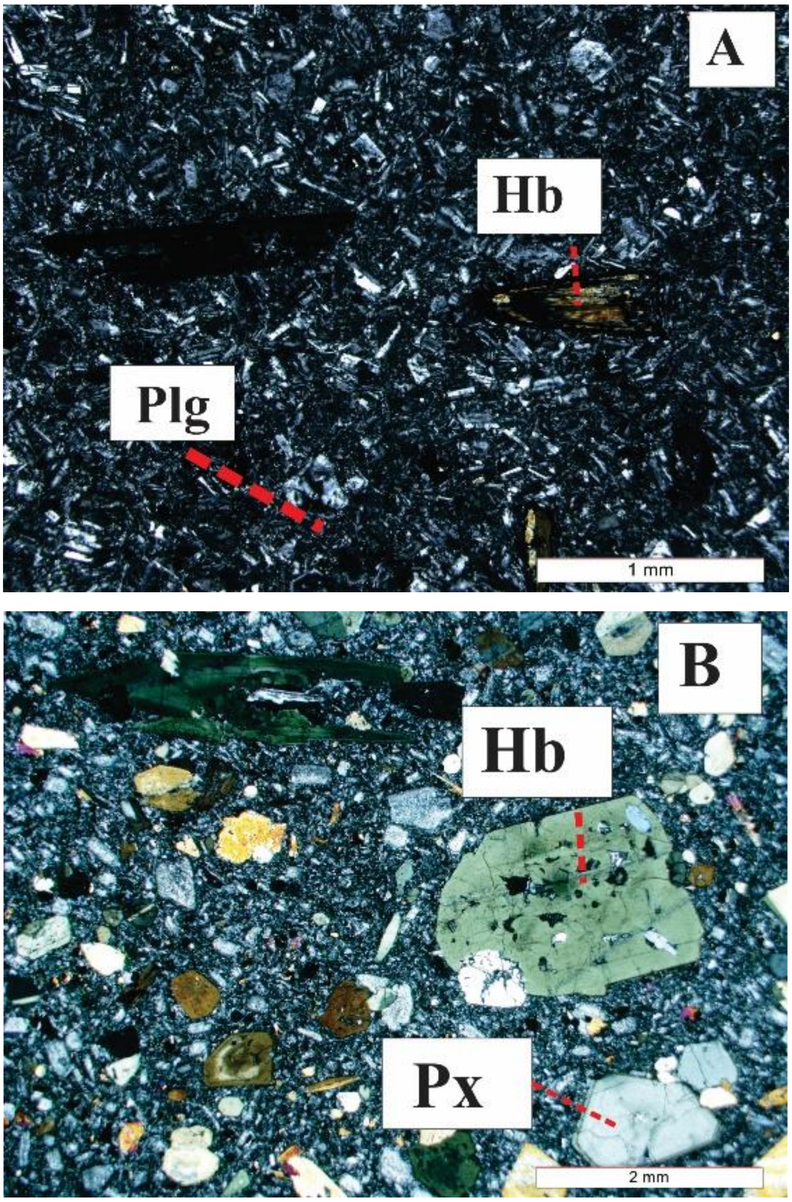


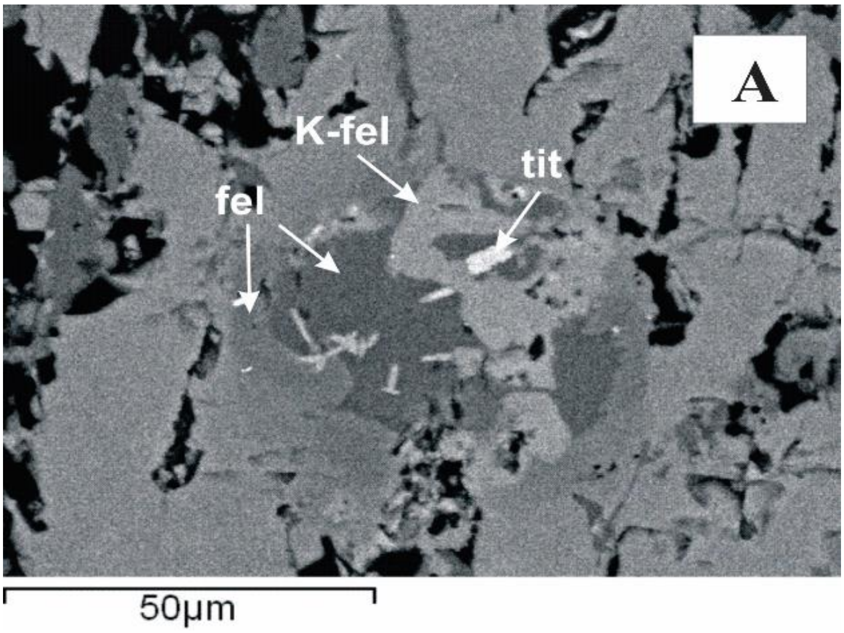
Figure 3: Photomicrographs of the studied rocks, in cross-polarized light a) porphyritic texture; amphibole and plagioclase phenocrysts within trachydacite; b) plagioclase, amphibole and pyroxene within basaltic andesite showing porphyritic texture. Mineral abbreviations are from Whitney and Evans (2010).

4. RESULTS

4.1 Petrography

Based on petrographic studies, the main mineral components of hypabyssal rocks in Torud-Ahmad Abad magmatic belt include hornblende, plagioclase and pyroxene (Fig. 3). Sericite, chlorite, calcite, apatite and magnetite are minor components. The size of plagioclases ranges between 2 to 12 mm and they display compositional zoning. Some plagioclase phenocrysts have been altered to secondary minerals such as calcite and sericite, which are seen as small patches or small grains in the core or margin of the plagioclase. This kind of alteration is more common in dacite and gives a dusty appearance to the rock. Plagioclase composition ranges from albite to labradorite. Amphiboles exhibit both normal and oscillatory zoning. Their composition ranges from Mg-hastingsite to Mg-hornblende. Pyroxenes range in composition from diopside to augite (Yousefi et al., 2017b). The studied rocks display porphyritic, glomeroporphyritic, granular and trachytic textures. Extension and shear stress have caused fragmentation of cumulative crystals in magma which results in glomeroporphyritic clots and accumulations that are brought up with the rise of the molten magma (Baker, 2008). Glomeroporphyries are believed to form in the melt due to reducing temperature and increasing viscosity.

Backscattered electron images of melt inclusions (Fig. 4) indicated that in the studied samples, MI are commonly small, rarely 1-5 μm in diameter, and their main mineral hosts are plagioclase and amphibole. The MI in these rocks were trapped during the simultaneous growth of the host mineral.



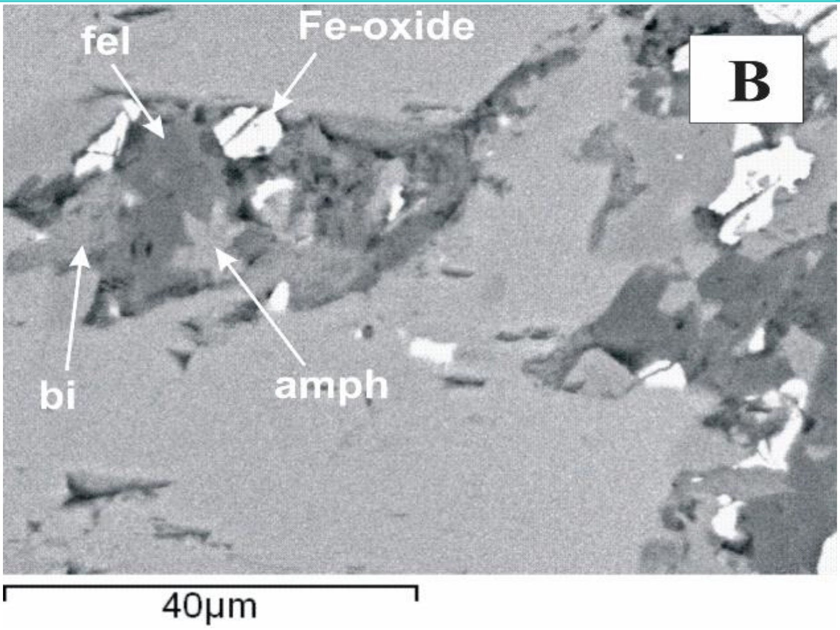


Figure 4: Backscattered electron image of melt inclusion in host mineral of plagioclase and amphibole.

4.2. Geochemical results

The chemical composition of melt inclusions was determined and representative results are presented in Table **1**. As shown, SiO_2 and Al_2O_3 constitute the main oxides in the MI composition with average values of 67.50 wt% and 18.68 wt%, respectively, followed by CaO (mean 5.90 wt%) and Na_2O (4.16 wt%). In detail, in andesite SiO_2 and Al_2O_3 exhibit ranges of 59.87-67.31 wt% and 20.59-26.67 wt%, respectively, while ranges of 0.29-6.73 wt% and 0.21-8.83 wt% were recorded for CaO and Na_2O, respectively.

On the other hand, in basaltic andesite and dacite, ranges of 47.95-67.49 wt% and 56.67-99.82 wt% were recorded for SiO_2, respectively, while a large variation was observed for Al_2O_3 with ranges of 0.66-33.22 wt% and 0.18-28.28 wt%, respectively. Regarding CaO and Na_2O, the average contents observed were 8.44 wt% (0.14-19.67 wt%) and 3.10 wt% (range 0.29-9.27 wt%) in basaltic andesite, while the corresponding mean values in dacite were 4.05 wt% (range n.d.-9.16 wt%) and 2.61 wt% (range 0.14-6.08 wt%), respectively. FeO, MgO, and K_2O showed lower contents with the exception of basaltic andesite where relatively higher contents of K_2O (mean 5.81 wt%) and MgO (mean 2.05 wt%) were observed.

The composition of melt inclusions analyzed in the dacitic, andesitic and basaltic andesitic rocks, range from andesite, basaltic andesite to dacite. The Harker diagrams of MI illustrate negative correlation of Al_2O_3 and CaO vs. SiO_2 pointing to crystal differentiation during crystallization of magma (Fig. 5).

Table 1: Composition of melt inclusions of the studied rocks. Sample 23 = andesite; sample 32 = basaltic andesite; sample 33 = dacite. Analyses given in wt%.

Sample	SiO2	Al2O3	FeO	MgO	CaO	Na2O	K2O	P2O5	BaO
23.1a.1	66.71	22.59	0.54	0.12	4.48	7.67	0.28	1.36	0.86
23.1a.5	62.46	21.82	0.41	0.53	6.33	6.77	0.34	0.54	0.8
23.1a.6	65.4	22.92	0.03	0.57	3.03	6.65	1.38	0.15	0.13
23.1a.7	59.87	26.67	0.02	0.07	6.73	7.73	0.24	0.06	1.25
23.1a.8	65.11	21.66	0.49	0.08	3.68	7.59	1.14	0.83	0.58
23.1a.9	67.31	21.23	0.03	0.29	1.89	8.83	0.77	0.13	0.36
23.1a.10	63.24	20.59	1.85	2.52	0.29	0.21	11.47	0.16	0.42
23.2a.1	61.83	23.7	0.14	0.28	5.67	7.84	0.32	0	0.51
23.2a.3	65.67	23.45	0.47	0.03	3.19	8.44	0.45	1.31	0.39
32.1a.1	63.04	25.52	0.55	0.68	0.69	11.93	0.14	1.05	0.12
32.1a.3	49.59	32.56	0.79	0.25	15.01	2.68	0.13	0.61	0.37
32.1a.4	55.11	3.93	8	14.13	19.22	1.13	0.26	0.96	0.82
32.1a.5	67.49	16.04	0.33	0.07	0.5	1.78	14.98	1.04	0.16
32.1a.6	63.12	19.49	0.34	0.21	0.62	0.29	17.68	0.57	0.19
32.1a.8	54.51	30.61	0.78	0.98	14.4	1.59	0.47	0.69	1.1
32.1a.9	57.37	26.99	0.27	0.12	6.51	6.87	3.18	0.12	1.42
32.1a.10	55.59	0.66	6.67	15.75	19.67	1.11	0.24	0.33	0.47
32.1a.11	63.23	18.53	0.67	0.42	0.14	1.69	14.9	0.32	0.74
32.2a.1	55.76	27.51	0.29	0.46	13.6	3.63	0.1	0.71	0.14
32.2a.2	62.11	23.64	0.46	0.11	3.53	9.27	0.41	0.74	0.27
32.2a.3	47.95	33.22	0.29	0.3	16.96	1.64	0.33	0.09	0.17
33.1.1	96.88	1.42	0.56	0.46	0.24	0.06	0.33	0	0
33.1.2	98.6	0.18	0.06	0.31	0	0.63	0.25	0	0
33.1.3	94.1	3.21	0.3	0.21	0.33	1.19	0.84	0	0
33.1.4	99.82	0.6	0.23	0.08	0.26	0.23	0.12	0	0
33.1.6	98.73	1.19	0.25	0.16	0.08	0.23	0.25	0	0
33.1.7	99.18	0.78	0.33	0.32	0.48	0.14	0.39	0	0
33.1.9	58.95	26.36	0.37	0.15	8.27	5.68	0.22	0	0
33.1.10	59.17	27.01	0.15	0.15	9.16	4.28	0.35	0	0
33.1.11	58.05	26.64	0.93	0.29	8.83	6.08	0.05	0	0
33.1.12	56.67	28.28	0.47	0.29	9	5.06	0.45	0	0

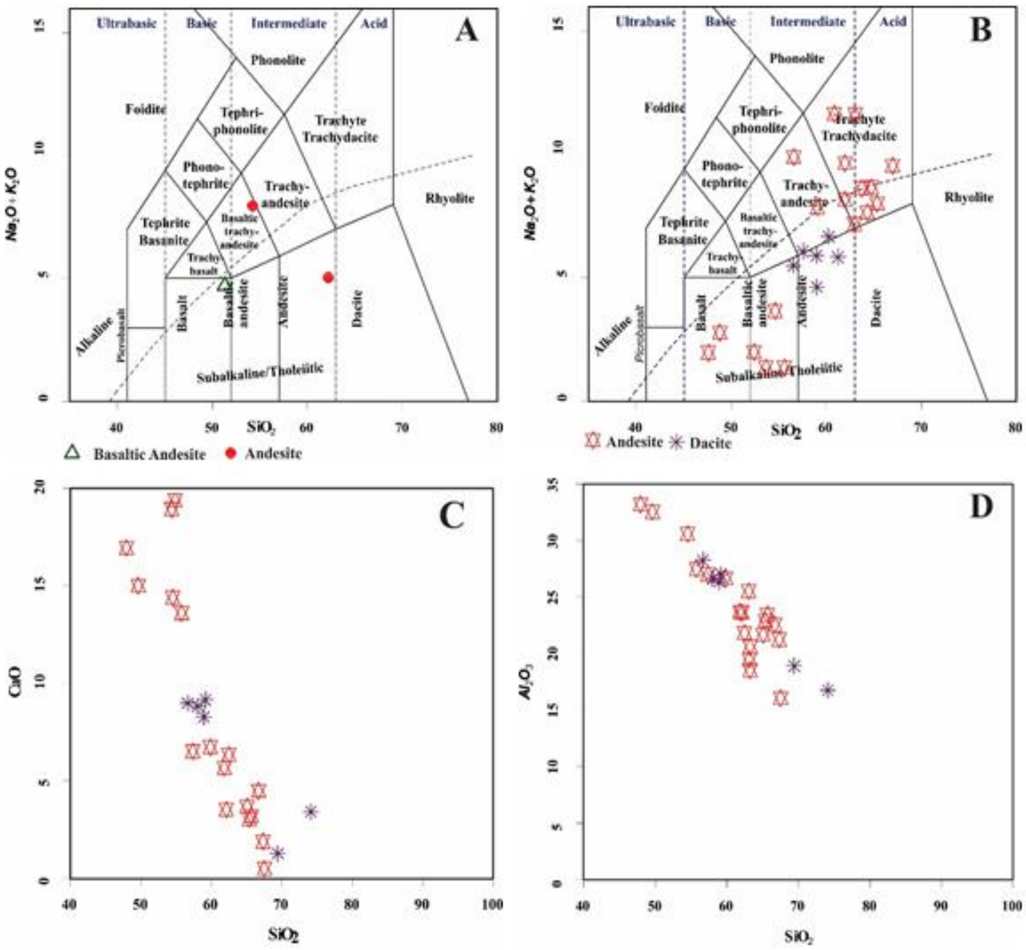


Figure 5: Classification diagram of rocks and melt inclusions. A: Composition of whole rocks. B: Composition of melt inclusions in plagioclase from andesite, dacite and basaltic andesite (Le Bas et al., 1986). C and D: Harker diagrams (1909).

5. DISCUSSION

Melt inclusions are hosted in many, virtually all, igneous-related minerals, but are mostly studied in those that are more abundant and/or better preserved and/or more visible. In felsic igneous rocks common host minerals are quartz and plagioclase, while in mafic/ ultramafic igneous rocks olivine, pyroxene and plagioclase are the main hosts (Cesare et al., 2015). Melt inclusions represent melts that are entrapped in crystallizing minerals and act as closed systems. Thus, they can give information about the primary melts and have the potential to become a fundamental tool for the study of crustal melting, crustal differentiation and even the generation of the continental crust (Cesare et al., 2015).

The mineral zoning as well as the range of mineral and MI compositions, suggest a complex magma petrogenesis. These rocks could be the result of mixing of various magmatic bodies. The wide range of MI compositions could arise from the mixing of different magmas that also enclose crystals from a shallow crystal mush during their ascent to the surface (Cassidy et al, 2015).

Based on Yousefi et al. (2017a, b), the significant factors of evolution of these magmas are magma mixing, fractional crystallization and crustal contamination while isotope geology showed that they have originated from the mantle. In particular, the dacites, which have more silica, originated from the melting of the subducted Neo-Tethyan oceanic slab (Sabzevar–Darouneh branch). According to Grondahl and Zajacz (2017), water is responsible for increasing the concentration of SiO_2 in silicate melts that equilibrate with mantle peridotite.

Based on the fact that the composition of the MI is similar to the composition of the host rocks, basaltic andesites and andesites are repeatedly generated from mantle magma batches during their ascent as they mix with resident magmas, fractionate and recycle older crystals.

6. CONCLUSIONS

The Torud–Ahmad Abad magmatic belt is located in the south-southeast of Shahrood in the northern part of the central Iran structural zone. Based on geochemical analysis, the studied rocks have chemical compositions varying from andesite, trachyandesite, basaltic andesite and dacite. Plagioclase, hornblende and pyroxene constitute the major minerals of these rocks.

The hypabyssal igneous intrusions of this region intruded into a thick sequence of Paleocene to middle Eocene volcanic and volcanosedimentary rocks. The melt inclusions in these rocks are small droplets of melt that are trapped in minerals during their growth or crystallization and their composition ranges from basaltic andesite, andesite to dacite.

Based on the composition of the melt inclusions and their host rocks from Torud-Ahmad Abad magmatic belt, basaltic andesites and andesite rocks are repeatedly generated from mantle magma batches during their ascent as they mix with resident magmas, fractionate and recycle older crystals.

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