



GEOCHRONOLOGY OF PLUTONIC ROCKS FROM THE SANANDAJ-SIRJAN ZONE, IRAN AND NEW ZIRCON AND TITANITE U-Th-Pb AGES FOR GRANITOIDS FROM THE MARIVAN PLUTON

ALI A. SEPAHI¹, HOSSEIN SHAHBAZI¹, WOLFGANG SIEBEL² and AHMAD RANIN¹

¹Department of Geology, Bu-Ali Sina University, Hamedan, Iran

²Department of Earth Sciences, University of Tübingen, Tübingen, Germany

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Abstract: The Sanandaj-Sirjan zone of Iran is a metamorphic belt consisting of rocks which were metamorphosed under different pressure and temperature conditions and intruded by various plutons ranging in composition from gabbro to granite. The majority of these granitoids formed along the ancient active continental margin of the Neo-Tethyan ocean at the southeastern edge of the central Iranian microplate. Geochronological data published in recent years indicate periodic plutonism lasting from Carboniferous through Mesozoic to late-Paleogene times (from *ca.* 300 to *ca.* 35 Ma) with climax activity during the mid- and late-Jurassic. The age constraints for plutonic complexes, such as Siah-Kouh, Kolah-Ghazi, Golpayegan (Muteh), Azna, Aligoodarz, Astaneh, Borujerd, Malayer (Samen), Alvand, Almogholagh, Ghorveh, Saqqez, Marivan, Naqadeh and Urumieh, clearly indicate the periodic nature of magmatism. Therefore, the Sanandaj-Sirjan zone preserves the record of magmatic activity of a complete orogenic cycle related to (1) Permocarboneous(?) rifting of Gondwana and opening of the Neo-Tethyan ocean, (2) subduction of the oceanic crust, (3) continental collision and (4) post-collision/post-orogenic activities. The formation of the Marivan granitoids, northwestern Sanandaj-Sirjan zone, for which we present U-Pb zircon and titanite ages of *ca.* 38 Ma, can be related to the collisional and post-collisional stages of this orogenic cycle.

Keywords: granitoid, Iran, Marivan, plutonic rocks, Sanandaj-Sirjan zone, U-Pb data

1. INTRODUCTION

As a major tectono-stratigraphic unit of Iran, the Sanandaj-Sirjan zone hosts abundant outcrops of plutonic rocks (**Fig. 1**). Major progress has been made in recent years in unravelling the ages of these complexes by U-Pb zircon geochronology (e.g., Ahmadi-Khalaji *et al.*, 2007, Shahbazi *et al.*, 2010, Mahmoudi *et al.*, 2011, Ahadnejad *et al.*, 2011, Esna-Ashari *et al.*, 2012, Alirezaei and Has-

sanzadeh, 2012). However, the obtained ages often differ from those obtained by earlier K-Ar and Rb-Sr studies (e.g., Valizadeh and Cantagrel, 1975; Braud, 1987; Masoudi, 1997; Baharifar, 2004; Baharifar *et al.*, 2004). This paper has two main objectives. The first is to provide a brief summary of radiometric ages of major plutons in the Sanandaj-Sirjan zone. Secondly, we present new geochronological data for granitoids in the Marivan area, northwestern Sanandaj-Sirjan zone, in order to constrain their temporal relationship with magmatism in the Sanandaj-Sirjan zone. Our study completes the U-Pb data

Corresponding author: A. Sepahi
e-mail: aasepahi@gmail.com

set of the northwestern Sanandaj-Sirjan zone, and, by combining these and other recently published data, the magmatic history of this zone is re-evaluated.

2. GEOLOGICAL SETTING

Following the classical work of Alavi (1994), the Zagros orogen of Iran is divided, from southwest to northeast, into three tectono-stratigraphic zones, *i.e.*, the Zagros fold and thrust belt, the Sanandaj-Sirjan zone or Zagros imbricate zone, and the Urumieh-Dokhtar magmatic arc (Fig. 1). The Sanandaj-Sirjan zone is ~1500 km long and ~150–200 km wide. It extends from northwest to southeast Iran and is considered as an ancient active continental margin. It can be divided into several sub-zones based on lithostratigraphy, structural and deformation history.

The Marivan area, situated between East Longitude 46°00' to 46°30' and North Latitude 35°20' to 35°40' (Fig. 2), lies within the highly deformed sub-zone of the Sanandaj-Sirjan zone. The major lithological units of this area include phyllites, schists, crystallized limestones, and meta-volcanic rocks intruded by mafic to felsic plutons. According to Azizi *et al.* (2011a), the plutons south of the Marivan area belong to the Songor-Baneh volcano-plutonic belt and are associated with the Zagros thrust fault. Ranin *et al.* (2010) and Azizi *et al.* (2011a) suggested similar petrological and geochemical affinities for Marivan and Zagros thrust fault plutonic rocks in areas such as Taa-Baysaran and Morvarid in Kordistan (near SD — Sanandaj on Fig. 1).

3. PREVIOUS RADIOMETRIC AGE DATA

K-Ar, Rb-Sr and Sm-Nd data

Valizadeh and Cantagrel (1975) obtained K-Ar mica ages between 63 to 90 Ma for plutonic rocks of the Alvand complex, Hamedan. Braud (1987) determined a similar K-Ar age of 64 ± 2 Ma for the porphyritic granites of this complex. More recently, K-Ar dating on amphibole, biotite and muscovite yielded ages between 135 and 70 Ma for the Alvand complex, and these ages were interpreted as cooling ages (Baharifar *et al.*, 2004). Valizadeh and Cantagrel (1975) also reported Rb-Sr ages between 68 to 89 Ma for the Alvand complex (Table 1) and a much older whole-rock Rb-Sr age of 144 ± 17 Ma for dioritic rocks of the Almogholagh complex (Table 1). Masoudi (1997) obtained Rb-Sr ages between 130 to 60 Ma for plutonic rocks from the Borujerd complex and an age of 98.9 ± 1.5 Ma for the Astoneh diorite (Table 1, AS — Astoneh on Fig. 1). The age of the Siah-Kuh complex has been estimated by the Sm-Nd isochron method at about 200 Ma (Arvin *et al.*, 2007). An A-type granitoid from the Piranshahr area has been dated at 41 ± 0.5 Ma by the Rb-Sr method (Mazhari *et al.*, 2009). Based on K-Ar chronology of various minerals (amphibole, biotite, muscovite and feldspar) and field observations, it was concluded that the Urumieh complex formed during two distinct episodes: the older diorite-granite suite emplaced between 100 and 92 Ma, whereas the younger granite suite was generated between 82 and 80 Ma (Ghahmghash *et al.*, 2009).

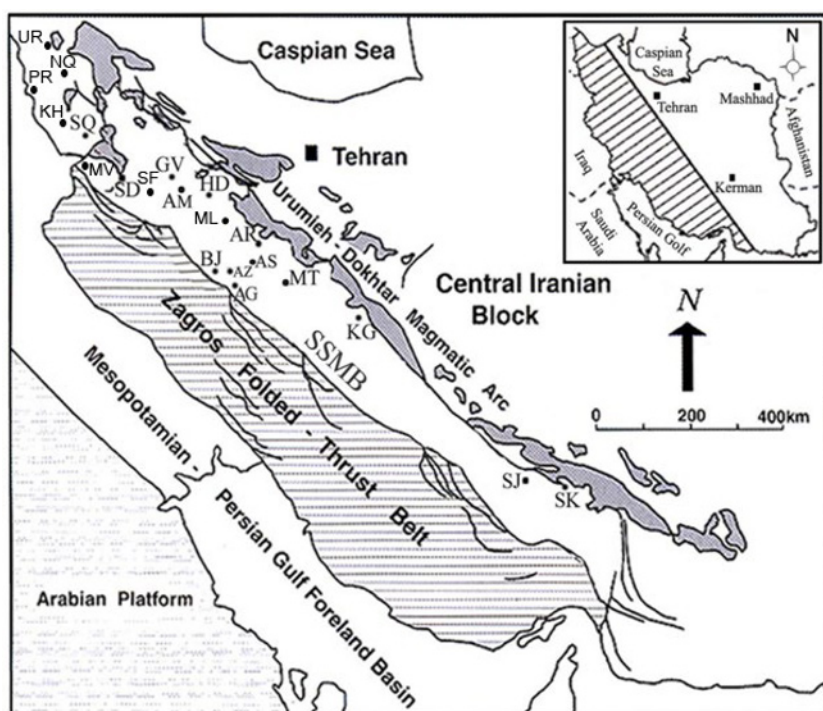


Fig. 1. Distribution of major plutonic bodies in the Sanandaj-Sirjan zone, Zagros orogenic belt, Iran, modified after Moazzen *et al.* (2004) and Sepahi (2008). Tectonic units after Alavi (1994, 2004) and Mohajjel and Fergusson (2000). Black points indicate major plutonic bodies of the Sanandaj-Sirjan zone. Abbreviations:

UR — Urumieh, NQ — Naqadeh, PR — Piranshahr, KH — Khalifan, SQ — Saqqez, MV — Marivan, SD — Sanandaj, SF — Soffiabad, GV — Ghorveh, AM — Almogholagh, HD — Hamadan (Alvand), ML — Malayer, AR — Arak, AS — Astoneh, BJ — Borujerd, AG — Aligoodarz, AZ — Azna, MT — Muteh, KG — Kolah-Ghazi, SJ — Sirjan and SK — Siah-Kuh.

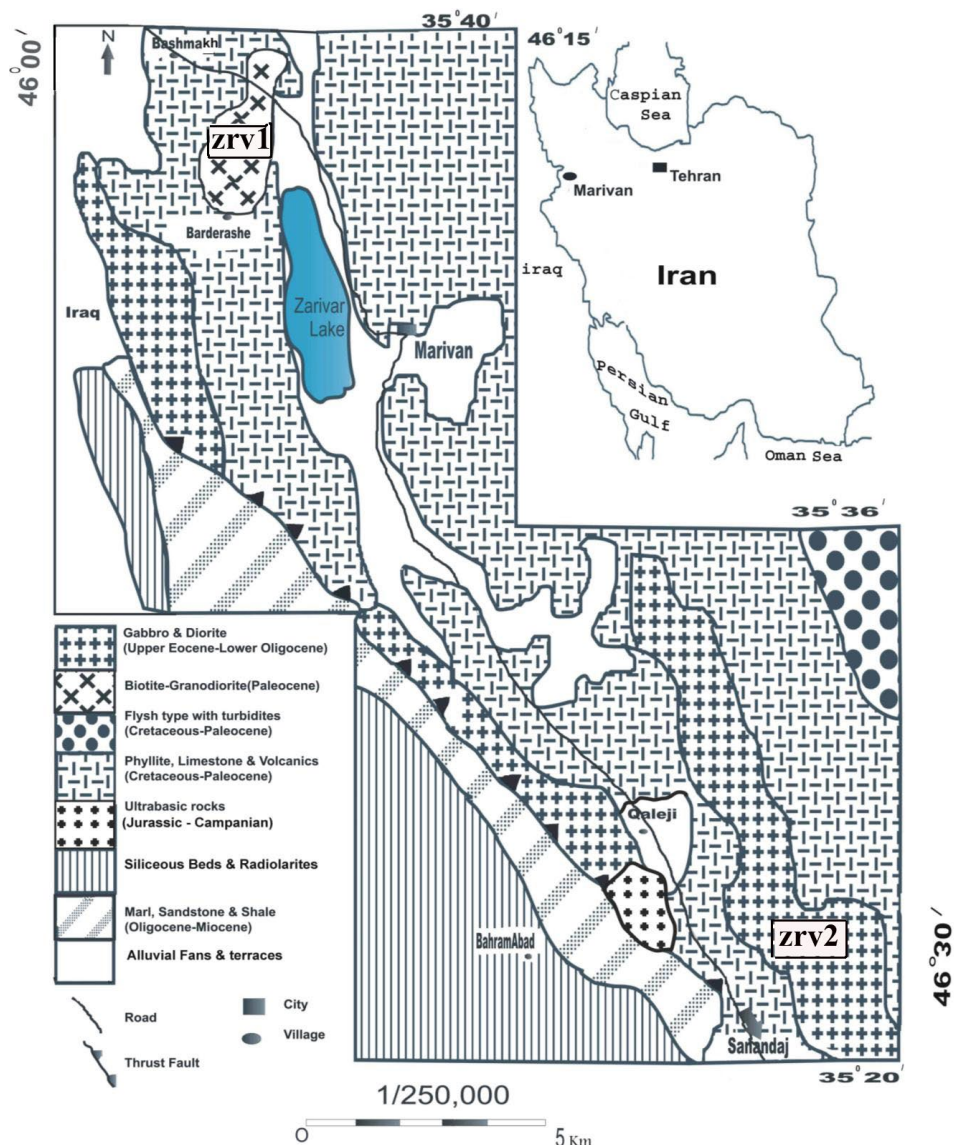


Fig. 2. Simplified geological map of the Marivan area.

U-Pb age data

In this section we briefly review the results of U-Pb studies, mainly published in recent years, for plutonic rocks of the Sanandaj-Sirjan zone (Table 2). The data can be broadly divided into three age groups. Relatively old U-Pb ages were reported for the Khalifan pluton (KH — Khalifan on Fig. 1). Zircon U-Pb SHRIMP and Pb-Pb sequential evaporation dating revealed a Carboniferous age of 315 ± 2 Ma for granites from this pluton (Bea *et al.*, 2011). This age was interpreted as magmatic crystallization age related to the Variscan orogeny in the region. Based on stratigraphic observations a Precambrian age was assigned to the Hasan-Robat granite by Mansouri-Esfahani *et al.* (2010). However, Alirezai and Hassanza-deh (2012) determined a Permian U-Pb age of

288.3 ± 3.6 Ma for this pluton (Table 2). They attributed the formation of this granite to the break-up of Gondwana and the opening of the Neo-Tethyan ocean between the Sanandaj-Sirjan and the Zagros zones during the Permian.

The Mesozoic era, mainly the mid-Jurassic to lower-Cretaceous appears to be the most intensive period of magmatism in the Sanandaj-Sirjan zone, and this is documented by numerous dating results (Table 2). LA-ICP-MS U-Pb zircon ages of the Malayer pluton span an age range between 187 and 162 Ma (mid-Jurassic) (Ahadnejad *et al.*, 2011). According to Ahmadi-Khaladji *et al.* (2007), the Boroujerd granitoid complex has similar U-Pb zircon ages of 172–169 Ma. U-Pb LA-ICPMS zircon data from granitoids of the Aligoodarz complex yield a crystallization age of *ca.* 165 Ma (Esna-Ashari *et al.*,

Table 1. K-Ar, Rb-Sr and Nd-Sm age data on major plutonic bodies of the Sanandaj-Sirjan zone, Iran.

Name of intrusive bodies	Method	Age (Ma)	References
Alvand norite	Rb-Sr	78–89	Valizadeh and Cantagrel (1975)
Alvand norite	K-Ar	89.1 ± 3	Valizadeh and Cantagrel (1975)
Alvand pegmatite	Rb-Sr	104 ± 3	Valizadeh and Cantagrel (1975)
Alvand pegmatite	K-Ar	82.8 ± 3	Valizadeh and Cantagrel (1975)
Alvand porphyroid granite	Rb-Sr	68 ± 2	Valizadeh and Cantagrel (1975)
Alvand porphyroid granite	K-Ar	63.8–80.8 ± 3	Valizadeh and Cantagrel (1975)
Almogholagh diorite	Rb-Sr	144 ± 17	Valizadeh and Cantagrel (1975)
Alvand porphyroid granite	K-Ar	64 ± 2	Braud (1987)
Borujerd older granite	Rb-Sr	130 ± 1.4	Masoudi (1997)
Borujerd diorite	Rb-Sr	117.2 ± 1.2	Masoudi (1997)
Borujerd older pegmatite	Rb-Sr	127.3 ± 1.3	Masoudi (1997)
		119.2 ± 1.3	
Astaneh diorite	Rb-Sr	98.9 ± 1.5	Masoudi (1997)
Borujerd younger granite	Rb-Sr	60–70 ± 0.7	Masoudi (1997)
Borujerd younger pegmatite	Rb-Sr	52 ± 0.5	Masoudi (1997)
Alvand porphyroid granite	K-Ar	81.8 ± 1.9	Baharifar <i>et al.</i> (2004)
Alvand pegmatite	K-Ar	74.7 ± 1.8	Baharifar <i>et al.</i> (2004)
Alvand quartz diorite	K-Ar	73.2 ± 3.1	Baharifar <i>et al.</i> (2004)
Alvand diorite	K-Ar	135.2 ± 3.1	Baharifar <i>et al.</i> (2004)
Siah-Kuh granitoids	Sm-Nd	199 ± 30	Arvin <i>et al.</i> (2007)
Piranshahr A-type granitoids	Rb-Sr	41 ± 0.5	Mazhari <i>et al.</i> (2009)
Urumieh diorite and granite	K-Ar	92–100	Ghalamghash <i>et al.</i> (2009)
Urumieh alkali granite and syenite	K-Ar	80–82	Ghalamghash <i>et al.</i> (2009)

Table 2. U-Pb radiometric age data on the major plutonic bodies of the Sanandaj-Sirjan zone, Iran.

Name of plutonic bodies	Age (Ma)	References
Borujerd quartz-diorite	170.7 ± 1.6	Ahmadi-Khaladji <i>et al.</i> (2007)
Borujerd granodiorite	169.6 ± 0.2	Ahmadi-Khaladji <i>et al.</i> (2007)
Borujerd granodiorite	171.3 ± 1.1	Ahmadi-Khaladji <i>et al.</i> (2007)
Borujerd granodiorite	170.7 ± 1	Ahmadi-Khaladji <i>et al.</i> (2007)
Borujerd monzogranite	171.7 ± 1.5	Ahmadi-Khaladji <i>et al.</i> (2007)
Borujerd pegmatite	170.7 ± 1.5	Ahmadi-Khaladji <i>et al.</i> (2007)
Piranshahr mafic plutonic rocks	40.7 ± 0.2	Mazhari <i>et al.</i> (2009)
Piranshahr granitic rocks	41.3 ± 0.8	Mazhari <i>et al.</i> (2009)
Alvand gabbro	166.5 ± 1.8	Shahbazi <i>et al.</i> (2010)
Alvand granite	163.9 ± 0.9	Shahbazi <i>et al.</i> (2010)
	161.7 ± 0.6	
Alvand leucogranite	154.4 ± 1.3	Shahbazi <i>et al.</i> (2010)
	153.3 ± 2.7	
Malayer pluton	162–187	Ahad-Nejad <i>et al.</i> (2011)
Borujerd plutonic Complex	~169	Mahmoudi <i>et al.</i> (2011)
Astaneh granitic pluton	~168	Mahmoudi <i>et al.</i> (2011)
Granites of the Alvand pluton	~165	Mahmoudi <i>et al.</i> (2011)
Gorveh pluton	157–149	Mahmoudi <i>et al.</i> (2011)
Hasan Salary I-type pluton	~109	Mahmoudi <i>et al.</i> (2011)
Hasan Salary A-type granite	~60	Mahmoudi <i>et al.</i> (2011)
Gosheh-Tavandash granite (near to BJ — Borujerd in Fig. 1)	34.9	Mahmoudi <i>et al.</i> (2011)
Taa-Baysaran gabbro-diorite in Zagros thrust zone southwest of Sanandaj	36.75 ± 0.51	Azizi <i>et al.</i> (2011a)
	36.63 ± 0.40	
Suffi-abad granite	149 ± 2	Azizi <i>et al.</i> (2011b)
	144 ± 3	
Khalifan granites	315 ± 2	Bea <i>et al.</i> (2011)
Aligoodarz granitoid complex	~165	Esna-Ashari <i>et al.</i> (2012)
Hasan-robot granite (near Muteh — MT in Fig. 1)	288.3 ± 3.6	Alirezai and Hassanzadeh (2012)
Naqadeh granite	41.85 ± 0.81	Mazhari <i>et al.</i> (2012)

2012). Inherited grains, spanning ages from *ca.* 180 Ma up to 2027 Ma, were also found in rocks from this complex, confirming the presence of Mesozoic and older Proterozoic crustal components in the source regions of these plutons (Esna-Ashari *et al.*, 2012). U-Pb dating results also demonstrate that the Alvand plutonic complex was generated during mid- and late-Jurassic. Gabbros of this pluton formed at 166.5 ± 1.8 Ma, granites between 163.9 ± 0.9 Ma and 161.7 ± 0.6 Ma, and leucogranites between 154.4 ± 1.3 and 153.3 ± 2.7 Ma (Shahbazi *et al.*, 2010). LA-ICP-MS U-Pb zircon ages of the Suffiabad granite range between 149 ± 2 and 144 ± 3 Ma (Azizi *et al.*, 2011b).

A third group of plutons is characterized by Paleogene ages. Mazhari *et al.* (2009) have concluded that the bimodal Piranshahr massif is composed of coeval but geochemically unrelated mafic intrusions (40.7 ± 0.2 Ma zircon U-Pb SHRIMP age) and felsic rocks (41 ± 0.5 Ma Rb-Sr whole-rock and 41.3 ± 0.8 Ma zircon U-Pb SHRIMP age). The granitic unit of the Naqadeh plutonic complex yields a zircon U-Pb SHRIMP age of 41.85 ± 0.81 Ma with two age groups of 98.5 ± 1.7 and 586.6 ± 13.1 Ma obtained from zircon cores (Mazhari *et al.*, 2012). Some gabbroic to dioritic bodies of the Zagros thrust zone between the Sanandaj-Sirjan zone and the Zagros fold-thrust-belt also have Paleogene ages of 36.75 ± 0.51 Ma and 36.63 ± 0.40 Ma (Azizi *et al.*, 2011a).

Various stages of plutonic activity in the Sanandaj-Sirjan zone were unravelled by the recent U-Pb age study of Mahmoudi *et al.* (2011). According to these authors, the Boroujerd pluton (169 Ma), the Astaneh pluton (168 Ma), and the Alvand pluton (165 Ma) formed during the mid-Jurassic period; a late Jurassic emplacement age was documented for the Ghorveh pluton (157–149 Ma); mid-Cretaceous (109 Ma) formation of older I-type granites of the Hasan Salary pluton near Saqqez, followed by Early-Paleocene (60 Ma) intrusion of younger A-type granites in the same pluton. The youngest magmatic event in the Sanandaj-Sirjan zone determined by Mahmoudi *et al.* (2011) was the intrusion of an I-type granite in the Gosheh-Tavandasht complex near Boroujerd at *ca.* 35 Ma.

Summarizing, presently existing U-Pb geochronological data indicate the predominance of Mesozoic ages for plutons in the Sanandaj-Sirjan zone and adjacent regions. Mesozoic ages between 170–140 Ma are most probably related to subduction of the Neo-Tethyan oceanic crust beneath the central Iranian micro-plate (micro-continent) to the northeast. Plutons with Paleogene ages between 60–35 Ma are more likely related to the collisional and post-collisional events in the region (see also Agard *et al.*, 2011 and Mahmoudi *et al.*, 2011). As cited by Mahmoudi *et al.* (2011), this younger magmatism may be the cause of reheating in the region so that K-Ar and Rb-Sr ages of most plutons are considerably younger compared to the U-Pb ages.

4. PETROGRAPHY AND U-PB GEOCHRONOLOGY OF THE MARIVAN PLUTON

Petrography and geochemistry

Plutonic rocks in the Marivan area can be divided into granitoids in the northwestern and gabbros and quartz diorites in the southeast part of the Marivan pluton. The first group includes granodiorites, monzogranites, and syenogranites that are intruded by aplitic and pegmatitic dykes. The country rocks are pelitic and calc-silicate hornfelses. The granodiorites have hypidiomorphic granular texture (Fig. 3a) and, in places, show myrmekitic and perthitic intergrowths. These rocks contain plagioclase (35–40%), K-feldspar (15–20%), quartz (25–30%) and biotite (15–20%) as major minerals, and apatite and zircon as accessory phases. Secondary chlorite, muscovite occur, as well. The monzogranite has hypidiomorphic granular texture except some rocks which are porphyritic. Dynamic metamorphic textures, such as undulated extinction in quartz and bending of biotite, are also locally developed as a result of deformation. The monzogranite contains quartz (~30%), plagioclase (25–30%), K-feldspar (30–35%) and biotite (10–15%). Apatite and zircon are accessory phases, and secondary minerals are sericite, epidote and chlorite. Both granodiorites and monzogranites contain mafic microgranular enclaves near their chilled margins. The syenogranites have hypidiomorphic granular texture, and in places, show myrmekitic intergrowths. Deformation induced textures can likewise be observed in these rocks. They contain quartz (30–35%), plagioclase (15–20%), K-feldspar (30–40%) and biotite (5–10%). Accessory phases are apatite, zircon and muscovite. Occasionally, microgranodioritic-microtonalitic and micaceous enclaves (restitic or xenolithic in origin) can be found in the syenogranites.

Based on the classification of Frost *et al.* (2001), the granitoids of the northwestern Marivan pluton are peraluminous and high-K calc-alkaline in composition (Ranin *et al.*, 2010), and they are calc-alkalic to alkalicalcic and magnesian according to the Frost *et al.* (2001) scheme of geochemical classification. Field observations, petrography and geochemical features indicate that the granitoids resemble S-type granites. According to Pearce *et al.* (1984) and Batchelor and Bowden (1985) they plot in the syn-collision granite fields.

The plutonic rocks of the southeastern Marivan pluton are composed of gabbros, diorites, and quartz-diorites. The country rocks are phyllites and metavolcanics. Gabbros have subhedral granular and poikilitic textures and contain plagioclase, clinopyroxene, and amphibole. Secondary epidote, uraltite, and calcite occur in these rocks. Diorites have subhedral granular texture and contain plagioclase and amphibole with minor clinopyroxene, biotite, and quartz. Titanite and apatite are accessory phases. Secondary minerals are epidote, uraltite, and chlorite. The quartz diorites have subhedral granular and intergranular textures and contain plagioclase, amphibole,

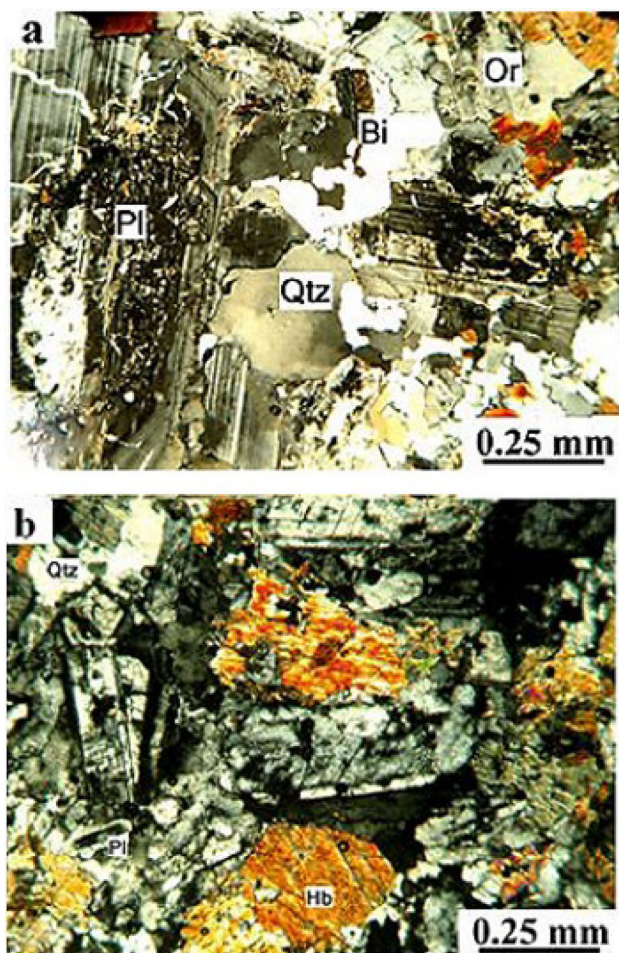


Fig. 3. Photomicrographs from two samples chosen for U-Pb geochronology; a) granodiorite northwestern Marivan pluton and b) quartz diorite from the southeastern Marivan pluton (Ranin, 2009 and Ranin et al. 2010). Abbreviations: Qtz — quartz, Pl — plagioclase, Or — orthoclase, Bi — biotite, Hb — hornblende.

quartz, and biotite with minor amounts of opaque minerals and orthoclase (Fig. 3b). Among the accessory minerals, titanite and apatite are frequently observed. Epidote and chlorite occur as secondary phases in these rocks. Based on Frost *et al.* (2001), the gabbro-diorite association of Marivan pluton has metaluminous, magnesian, and calcic composition and geochemical features of I-type calc-alkaline rocks (Ranin *et al.*, 2010).

U-Pb zircon and U-Th-Pb titanite dating of the Marivan granitoids

Analytical methods

Two granitoid samples (one granodiorite from the northwestern Marivan pluton, and one quartz-diorite from the southeastern part of the pluton, each 5–7 kg in weight) were crushed in a jaw crusher. Zircon and titanite grains were separated using a wet shaking table, a Frantz magnetic separator and heavy liquids and were finally

selected by handpicking under a binocular microscope. Zircon grains studied by cathodoluminescence (CL) imaging were mounted on epoxy resin and polished down to expose the grain interiors. CL images were obtained using a microprobe JEOL JXA-8900RL at the University of Tübingen. We followed the methods described in Chen *et al.* (2002) for sample preparation and analyses. For ^{235}U - ^{205}Pb - ^{232}Th analyses, single grains or 2–5 morphologically identical grains of zircons or titanites were washed in warm 7 N HNO_3 and 6 N HCl before a mixed ^{205}Pb - ^{235}U - ^{232}Th tracer solution was added to the fractions. Dissolution was performed in PTFE vessels in Parr digestion bombs (Parrish, 1987) at 210°C for 7 days in 22 N HF and for 1 day in 6 N HCl .

Separation and purification of U, Th and Pb were carried out on Teflon columns with a 40 μl bed of AG1-X8 (100–200 mesh) anion exchange resin. All isotope measurements were made on a Finnigan MAT 262 mass spectrometer at the University of Tübingen. Pb was loaded with a Si-gel onto a Re-filament and was measured at $\sim 1300^\circ\text{C}$ in a single-filament configuration, while U and Th were loaded with H_2O onto a Re-filament and were measured in a double-filament configuration. Total procedural Pb, U and Th blanks were <10 pg. A factor of 0.1% per atomic unit for instrumental mass fractionation was applied to all Pb analyses, using NBS 981 as reference material. Initial common Pb remaining after correction for tracer and blank was corrected using common lead values from Stacey and Kramers (1975) model. The Th-U-Pb data were evaluated using the *Pbdat* program (Ludwig, 1988), and regression of Th-U-Pb discordia was conducted with Isoplot 3.0 (Ludwig, 2003). All errors were given at a 95% confidence level (2σ).

U-Pb zircon and Th-U-Pb titanite ages of the Marivan pluton

Granodiorite sample zrv1 was chosen for U-Pb zircon dating and quartz-diorite sample zrv2 for U-Th-Pb titanite dating. The analytical data are listed in Tables 3 and 4, respectively. Zircons are euhedral to subhedral with short prismatic or isometric crystal faces. Grains are generally <200 μm in diameter and brownish to colorless transparent. Most grains imaged by CL clearly show well-developed magmatic oscillatory zonation but some grains show sector zoning especially in their interior parts (Fig. 4). The titanite grains are yellow and brown colored crystals and more than 100 μm in diameter.

The different zircon fractions plot close to the lower intercept of the discordia line (Fig. 5). From the alignment of the data points in the Concordia diagram, a lower discordia intercept age of 37.9 ± 1.9 Ma can be calculated. This age is interpreted to provide the closest approximation to the crystallization age of the granodiorite. From the U-Th-Pb titanite data (Table 4) an age range from 39.3 to 35.6 Ma is obtained. The average age of these grains is 37.5 ± 8 Ma (Fig. 6). This age is interpreted as crystallization age of the quartz-diorite.

Table 3. U-Pb zircon isotope composition (ID-TIMS data) of zircon fractions from granodiorite sample Zrv1 from the NW Marivan pluton.

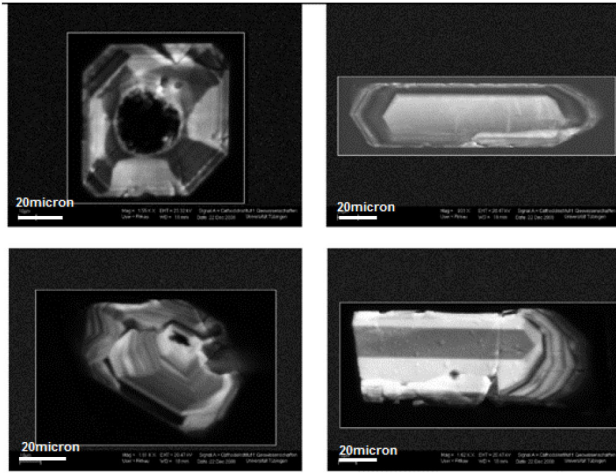
Sample/ Sample fraction	Sample weight (mg)	Atomic ratios							Calculated apparent ages (Ma)		
		$^{206}\text{Pb}/^{204}\text{Pb}$	U (ppm)	Pb (ppm)	$^{208}\text{Pb}^*/^{206}\text{Pb}^*$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{207}\text{Pb}^*/^{206}\text{Pb}^*$	$^{206}\text{Pb}^*/^{238}\text{U}$	$^{207}\text{Pb}^*/^{235}\text{U}$	$^{207}\text{Pb}^*/^{206}\text{Pb}^*$
Zrv1-1	0.031	306.9	1779	13	0.06605	0.005972 ± 34	0.03860 ± 69	0.04688 ± 77	38.4	38.5	42.7
Zrv1-2	0.027	871.9	781	7	0.05847	0.007015 ± 59	0.04740 ± 98	0.04901 ± 85	45.1	47	148.3
Zrv1-3	0.023	1684	1232	8	0.08478	0.006117 ± 80	0.0405 ± 17	0.0480 ± 19	39.3	40.27	97.9
Zrv1-4	0.021	292.9	457	4	0.15634	0.006204 ± 36	0.04056 ± 87	0.04742 ± 94	39.9	40.4	70.4
Zrv1-5	0.016	246.2	742	6	0.12157	0.006418 ± 61	0.0427 ± 21	0.0420 ± 23	41.24	42.4	109.3

All errors quoted are 2σ absolute uncertainties and refer to the two last digits; * — radiogenic; zircon grain size varies from 80–180 μm .

Table 4. Th-U-Pb titanite isotope composition (ID-TIMS data) of titanite fractions from quartz diorite sample Zrv2, SE Marivan pluton.

		Atomic ratios								Calculated apparent ages (Ma)				
Sample/ Sample fraction	Sample weight (mg)	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$ corr.	U (ppm)	Th (ppm)	Pb (ppm)	$\frac{^{208}\text{Pb}^*}{^{206}\text{Pb}^*}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}^*}{^{206}\text{Pb}^*}$	$\frac{^{208}\text{Pb}}{^{232}\text{Th}}$	$\frac{^{206}\text{Pb}^*}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}^*}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}^*}{^{206}\text{Pb}^*}$	$\frac{^{208}\text{Pb}^*}{^{232}\text{Th}}$
Zrv2-1	0.0545	46.5	200.4	217.8	4	0.340574	0.000582 ± 12	0.0375 ± 75	0.0468 ± 91	0.00176 ± 12	37.4	37.4	39.8	35.6
Zrv2-2	0.0372	49.3	237.1	234.1	4.8	0.325155	0.00612 ± 14	0.039 ± 16	0.047 ± 19	0.00195 ± 23	39.3	39.3	39.3	39.3
Zrv2-3	0.0689	28.6	53	69.6	2.3	0.436057	0.00563 ± 16	0.036 ± 20	0.047 ± 25	0.00182 ± 23	36.2	36.2	38.1	36.9

All errors quoted are 2σ absolute uncertainties and refer to the two last digits; * — radiogenic; titanite grain size varies from 120–300 μm .

**Fig. 4.** Cathodoluminescence (CL) images of zircon grains from quartz-diorite sample Zrv1, pluton of the southeast of Marivan.

5. DISCUSSION

Zircon and titanite closure temperature consideration

Zircon has a higher closure temperature for U-Pb isotope system than titanite, therefore it can record the time of crystallization of granitoid magmas. On the other hand, titanite can crystallize or re-equilibrate in a variety of conditions and hence records the time when it was last closed for U-Pb. The closure temperature for U-Pb isotope system in titanite is still debated but is considered around 600°C to 712°C as the most appropriate range

(Zhang and Schärer, 1996; Sun *et al.*, 2012). Zhang and Schärer (1996) and Pidgeon *et al.* (1996) shown that the closure temperature increases with the grain size of titanites. Zircon ages from the same rock or from different rocks in the same terrane might be expected to be older than titanite ages. In the Marivan pluton zircon and titanite ages are in good agreement. But, given that these minerals were taken from different rock-types, we cannot compare their closure system behavior.

Chronology of magmatism in the Sanandaj-Sirjan zone

For more than 40 years, the Sanandaj-Sirjan zone has been considered as an ancient continental margin, but except for few studies (e.g., Valizadeh and Cantagrel 1975), radiometric data on plutons of this zone have been published only in the recent years. The radiometric ages for plutonic rocks were obtained using various methods such as K-Ar, Rb-Sr, Nd-Sm and U-Pb (e.g., Valizadeh and Cantagrel, 1975; Braud, 1987; Baharifar *et al.*, 2004; Masoudi, 1997; Arvin *et al.*, 2007; Ahmadi-Khaladji *et al.*, 2007; Mazhari *et al.*, 2009; Ghalamghash *et al.*, 2009; Shahbazi *et al.*, 2010; Bea *et al.*, 2011; Ahadnejad *et al.*, 2011; Azizi *et al.*, 2011a; Mazhari *et al.*, 2012; Azizi *et al.*, 2011b; Mahmoudi *et al.*, 2011; Alirezai and Hassanzadeh, 2012; Esna-Ashari *et al.*, 2012). These data indicate that extensive plutonism in the region occurred during the Mesozoic. On the basis of recently published data and our new U-Pb dating, it can be established that plutonism in the region occurred over a considerably long period of time (from *ca.* 300 to *ca.* 35 Ma) but episodic-

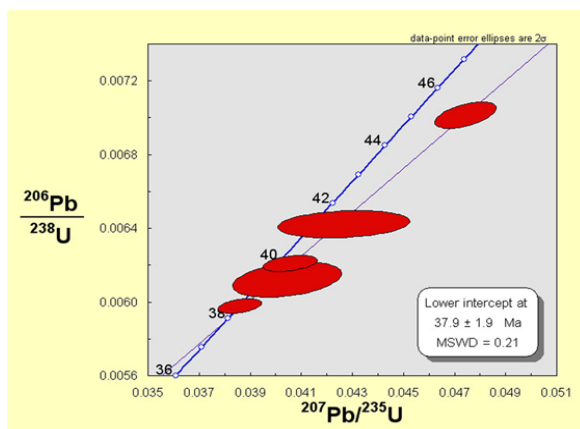


Fig. 5. U-Pb concordia diagram for zircons from granodiorite sample Zrv1, NW Marivan pluton.

ly with periods of intense activities ranging from *ca.* 170 to *ca.* 140 Ma and 60 to 35 Ma, although minor plutons with older Carboniferous and Permian ages has been reported, as well. Magmatism can be attributed to the northward subduction of the Neo-Tethyan oceanic crust beneath the central Iranian microplate, *i.e.* southern part of Eurasia, and to the later collision of the Afro-Arabian and Eurasian plates. Thus, the most intensive period of plutonism between 170 and 140 Ma can be explained by subduction-related processes. Plutons with ages between 60 and 35 Ma are possibly formed during collisional/post-collisional magmatic activities. Therefore, considering the plate tectonic model, magmatism at various stages of the Wilson cycle from rifting (Hasanrobat A-type granites, Alirezaei and Hassanzadeh, 2012) to spreading of oceanic crust of Neo-Tethys (Kermanshah ophiolitic complex as its remnants, Saccani *et al.*, 2013), subduction of the Neo-Tethys (gabbroic to granitic plutonic complexes in different parts of the Sanandaj-Sirjan zone, such as Alvand pluton near Hamedan) and subsequent collisional/post-collisional plutonism (plutons near to Sanandaj and Marivan areas) can be traced in different parts of the Sanandaj-Sirjan zone as a magmatic-metamorphic belt extending from NW to SE of Iran.

6. CONCLUSIONS

Presently existing radiometric ages demonstrate that the Sanandaj-Sirjan zone experienced periodic plutonic activity from the Carboniferous through the Mesozoic to the Paleogene (*ca.* 320 to *ca.* 35 Ma). Thus, the Sanandaj-Sirjan zone gives evidence of magmatic activities during a complete Wilson cycle related to rifting of Gondwana and opening of the Neo-Tethys during Permian-Carboniferous times, subduction of this ocean, continental collision, and post-collision/post-orogenic activities. Ages between 170–140 Ma are related to subduction of Neo-Tethyan oceanic crust beneath the central Iranian micro-plate to the northeast. Plutons with ages between 60–35 Ma are

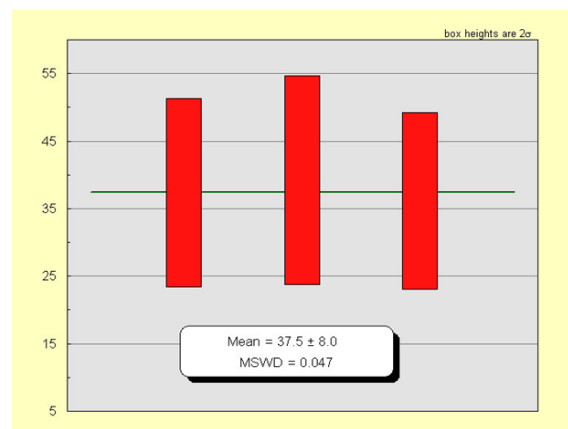


Fig. 6. Results of Th-U-Pb dating for titanites from quartz diorite sample Zrv2, SE Marivan pluton. Three titanite fractions yield a average $^{206}\text{Pb}/^{238}\text{U}$, $^{205}\text{Pb}/^{235}\text{U}$ and $^{208}\text{Pb}/^{232}\text{Th}$ ages of $37.5 \pm 8 \text{ Ma}$ (calculated from data shown in Table 4).

related to collisional and post-collisional events in the region. The Marivan plutonic rocks for which a U-Pb age of $\sim 38 \text{ Ma}$ was established can be related to this collision to post-collision magmatic event. This age is similar to those of Taa-Baysaran rocks (35–37 Ma, Table 1) which may indicate a similar magmatic history in both regions.

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