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# Zircon U-Pb geochronology and emplacement history of intrusive rocks in the Ardestan section, central Iran

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## ABSTRACT

The Urumieh-Dokhtar Magmatic Arc (UDMA) is part of the Alpine–Himalayan orogenic belt and interpreted to be a subduction-related Andean-type magmatic arc. Along this belt, Eocene volcanics and some gabbroic to granitic bodies crop out. The main rock types of the studied intrusion are granite, granodiorite, and diorite. They have geochemical features typical of magnesian, calc-alkaline, metaluminous to slightly peraluminous granites and I-type intrusive rock that have a strong enrichment in Large-Ion Lithophile (LIL) elements (*e.g.* Rb, Ba, Sr), and a depletion in High Field Strength (HFS) elements (*e.g.* Nb, Ti, P), typical of subduction-related magmas. Zircon U-Pb dating was applied to determine the emplacement ages of the different intrusions in the Ardestan area. Among them the Kuh-e Dom diorite is  $53.9 \pm 0.4$  Ma old; the Kuh-e Dom granodiorite is  $51.10 \pm 0.4$  Ma old; the Mehrabad granodiorite is  $36.8 \pm 0.5$  Ma old, the Nasrand granodiorite is  $36.5 \pm 0.5$  Ma old, the Zafarghand granodiorite is  $24.6 \pm 1.0$  Ma old, and the Feshark granodiorite is  $20.5 \pm 0.8$  Ma old. These results delineate more accurately the magmatic evolution related to the Neotethyan subduction from the Lower Eocene to Lower Miocene, and the subsequent Zagros orogeny that resulted from the Arabia-Eurasia collision. The emplacement of these intrusive rocks inside the UDMA, which has a close relationship with the collisional orogeny, is transitional from a subduction-related setting to post-collisional setting in the Ardestan area.

**KEYWORDS** | Zircon. Geochronology. Ardestan. Urumieh-Dokhtar Magmatic Arc belt. Iran.

## INTRODUCTION

The NW-SE trending Zagros Mountains in Iran are a member of the Alpine-Himalayan orogenic belt and represent one of the youngest continental collision zones on Earth. The Zagros orogeny consists of three NW-SE trending parallel subdivisions from Northwest to Southeast: the Zagros Fold-Thrust Belt (ZFTB), the adjacent Sanandaj-Sirjan Zone (SSZ), and the Urumieh-Dokhtar Magmatic Arc (UDMA) (Alavi, 2004). The tectonic history of the Tethyan region has been studied by

many authors (*e.g.* Stöcklin, 1974; Berberian and King, 1981; Mohajjel *et al.*, 2003; Agard *et al.*, 2011). From the Late Precambrian up to the Permian, part of Gondwana was separated from the Eurasian Plate by the Paleo-Tethys. During the Middle to Late Triassic, during the closure of the Paleo-Tethys in the North, rifting in the continental plate along the Zagros thrust zone occurred, resulting in the opening of a new ocean, the Neo-Tethys. During the Triassic–Jurassic, following the closure of Paleo-Tethys, the oceanic crust of Neo-Tethys started to subduct beneath the Eurasian Plate. This subduction progressively closed

the Neo-Tethys ocean and during the terminal collision formed the Zagros orogenic belt of Iran (Berberian and King, 1981; Alavi, 2004).

Volcanism in the UDMA initiated during the Eocene and continued throughout this period (Berberian and King, 1981). Its composition has a common calc-alkaline to shoshonitic and alkaline affinity with geochemical and petrological features similar to those of Andean-type magmatism (*cf.* Berberian *et al.*, 1982). The oldest igneous rocks in the UDMA are the calc-alkaline Shir-Kuh granitic complex, which cut across Upper Jurassic formations and are overlain unconformably by Lower Cretaceous fossiliferous limestone exposed in the southeastern margin of central Iran (Nabavi, 1972; Hajmolla-Ali *et al.*, 2000). The youngest rocks in the UDMA consist of lava flows and pyroclastics which form Pliocene to Quaternary volcanic cones with alkaline to calc-alkaline compositions (Berberian and Berberian, 1981). It is suggested that the Plio-Quaternary volcanism formed as a result of: i) the modification of the geothermal gradients due to uplift and erosion, ii) the strike-slip shearing motion created by differential movement of fault blocks due to the continued convergence of Arabia and Eurasia, and iii) the existence of large strike-slip faults, which developed a region of tension at both ends of these blocks (Berberian and King, 1981).

The collision has been recently studied in terms of geophysics, kinematics, and neotectonics. It is generally admitted that the Neo-Tethyan subduction started during the Triassic in Iran (Berberian and Berberian, 1981; Wilmsen *et al.*, 2009; Chiu *et al.*, 2013). The timing of its ending, and the onset of the Arabia-Eurasia collision, has long been a subject of debate. Timing estimates of the collision varies from ~65 to ~5Ma, based on a wide variety of presumed geologic responses to collision, such as:

i) ophiolite obduction in the Late Cretaceous and coeval development of a foreland basin on the Arabian margin (Berberian and King, 1981; Alavi and Mahdavi, 1994);

ii) late Eocene as based on structural, lithological, and palaeobiogeographical evidences from both sides of the original Arabia-Eurasia suture (Allen and Armstrong, 2008; Allen, 2009);

iii) early to Mid- Miocene transition from marine to non-marine sedimentation (McQuarrie *et al.*, 2003);

iv) late Miocene/Pliocene influx of coarse clastics into the foreland basin, rapid cooling in the Alborz Mountain, and rapid subsidence of the Caspian Sea (McQuarrie *et al.*, 2003);

v) absence of sedimentation during late Eocene-Oligocene in western part of Central Iran, suggesting that

the collision began between 35-25Ma, whereas oceanic subduction is still active (Agard *et al.*, 2005);

vi) emplacement of the Kermanshah ophiolite, that was probably an ancient oceanic core produced by large oceanic detachment faults, indicates that final closure of the Neo-Tethys Ocean occurred in the Late Miocene (Ao *et al.*, 2016).

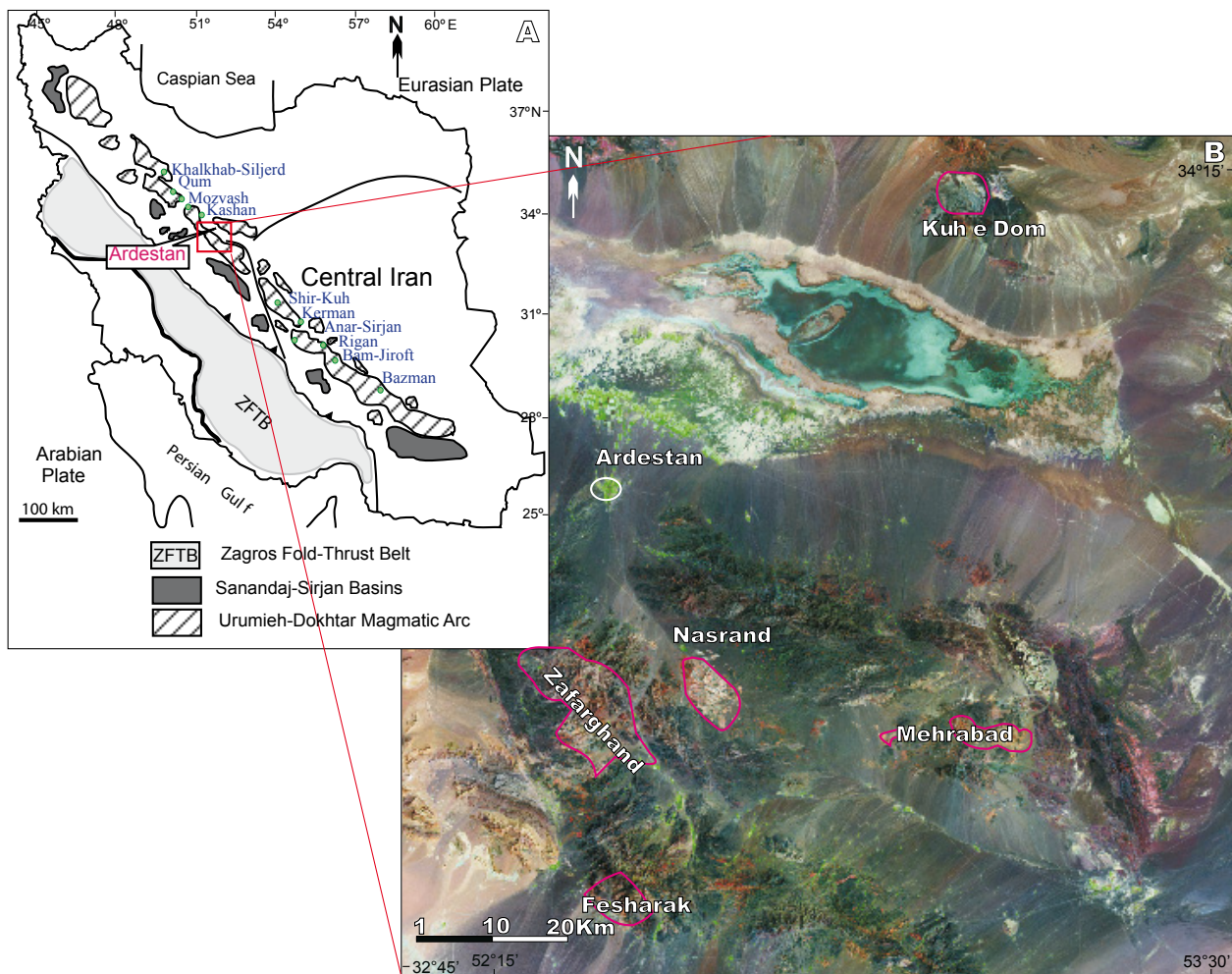
More recently, Ballato *et al.* (2011) proposed a two-stage collision model that involves an initial collision in the Late Eocene and an acceleration of the regional deformation in the Early Miocene.

The precise timing of collision between Arabia and Eurasia is still controversial and the geological history of the magmatic arcs in the Zagros orogenic belts in Iran is still poorly known. The reconstruction of tectonic and magmatic episodes requires a precise knowledge of their radiometric ages and the characterization of the petrogenetic processes. An increasing number of geochronological results has been published in the last decade for various rock units in Iran, whereas radiometric age constraints on the timing of plutonism in the UDMA are scarce. The aim of this study is to constrain the timing of the emplacement of the Kuh-e Dom, Mehrabad, Nasrand, Zafarghand, and Feshark intrusive rocks located in the middle part of UDMA. Achieving this we seek to provide clues about the geodynamic history of the Ardestan magmatic segment, to address some of the most important questions regarding the genesis of the intrusive rocks in the UDMA.

## GEOLOGICAL OVERVIEW

### Kuh-e Dom

The Kuh-e Dom intrusion, about 40km<sup>2</sup> in size, is located 110km to the northeast of Ardestan in central Iran, and is situated in the eastern part of the UDMA belt (Fig. 1). It can be divided into two main magmatic units, a mafic-intermediate unit and a felsic unit. The mafic-intermediate unit is exposed in the eastern, southern, and northern parts of the felsic unit, forming the marginal parts of the intrusion and includes gabbro-diorites, monzogabbro, monzodiorite, and monzonite. The felsic unit includes granite, granodiorite, and quartz monzonite with associated mafic microgranular enclaves of the same composition as the mafic-intermediate unit (Sarjoughian *et al.*, 2012a; Kananian *et al.*, 2014). The surrounding rocks of the Kuh-e Dom intrusion are mainly Eocene andesitic and rhyolitic lavas, Paleozoic phyllites and schists, and Cretaceous limestones. Paleozoic phyllites and schists are the oldest exposed rocks to the West of the intrusive rocks. The Cretaceous limestones are at its western and



**FIGURE 1.** A) The location of the study area in a simplified geological map of Iran and B) Location of the studied intrusive rocks plotted onto a satellite image.

southern sides, and the lower Eocene volcanic rocks at its eastern side. The country rocks are altered at the pluton's margins and the contact metamorphosed locally forming skarn and hornfels. The studied intrusion is cut by dikes that can be divided into the following categories: i) felsic dikes, including porphyric microgranite, porphyritic microgranodiorite, and aplite; ii) intermediate-mafic dikes, including phonolite, basanite, and trachyandesite. These dikes have a thicknesses ranging from 50cm up to 20m (Sarjoughian *et al.*, 2012b).

### Mehrabad

The Mehrabad intrusion is located in the Southeast of Ardestan, between 33°9'–33°13'N and 52°54'–53°2'E. This intrusion forms an elongated, East-West trending stock-like intrusive mass and crops out in two localities, Sohyle Pakuh at the East side and Hajiabad at the West side (Fig. 1). The Sohyle Pakuh intrusion includes granodiorite and subordinates monzonite and diorite, which may show

either gradational or intrusive relations. The Hajiabad intrusion is composed of granodiorite and granite, and less common tonalite that has gradational contacts. An undifferentiated tectonic mélangé is the oldest exposed rocks, consisting of spilite, basalt, andesite, radiolarite, and Cretaceous to early Paleocene pelagic sedimentary rocks in contact with the intrusive rocks. Cretaceous *Globotruncana* limestones with chert are interbedded with this mélangé zone. The Eocene sequence consists of andesite, dacite, and tuffite cut by intrusive rocks. This extrusive rocks are metamorphosed in the contact with the intrusion and the grade of contact metamorphism is generally within the albite-epidote hornfels facies.

### Nasrand

The Nasrand intrusion covers an area of ca. 28km<sup>2</sup> at 52°33'–52°34'E and 33°13'–33°15'N, to the Southeast of Ardestan (Fig. 1). The main rock types are granite and granodiorite, gradually transitioning into granodiorite

along the western margin of the intrusion. The undeformed granitic rocks are generally light grey to pink in color and have an elliptical shape. The granitic rocks intrude older rhyolite, dacite, and andesite rocks of Eocene age; consequently, field relationships indicate a post-Eocene emplacement age. This intrusion is cut by numerous Northeast-Southwest trending dark grey dioritic and gabbroic dikes 50 to 100cm in thickness. The alteration of the intrusion is not strong, with only weak epidotization and chloritization.

### Zafarghand

The Zafarghand intrusive rocks are located in the South of Ardestan, between 52°18'E to 52°30'E and 33°N to 33°12'N. The studied intrusion is the largest intrusive body in the Ardestan area and forms a markedly elongated body with a NW-SE direction, following an earlier fault trend (Fig. 1). The Zafarghand intrusive rocks include mafic to felsic intrusive bodies ranging in composition from gabbro to diorite, granodiorite and granite. The studied complex intruded Eocene volcanic rocks, including basalt, basaltic andesite, andesite, latite, dacite, rhyolite, and volcanoclastic rocks, such as tuff and ignimbrite. The contact with these volcanic rocks is marked by albite-epidote hornfels to hornblende hornfels facies. Granodiorite is the most abundant lithology followed by diorite. To the Northwest, diorite is transitional to more felsic rocks (granodiorite), while to the Southeast, diorite forms the margin of the pluton. It takes about 50 percent of the pluton and is light grey. Granitic rocks are found in the northern and northwestern parts of the complex and are light cream to white. The contacts between granites and granodiorite are typically gradational, suggesting *in situ* magma differentiation as the main process. Sometimes granites occur as leucocratic dikes or small stocks intruding the granodiorites. Gabbros form the smallest volume of the intrusive rocks in the central zone and are black to dark grey. They are surrounded by granodiorites and diorites with generally sharp contacts. Occurrence of veins of granodioritic magma in the gabbroic rocks, shows that gabbroic rocks are older than granodioritic rocks. Fine-grained, mafic microgranular enclaves, of diorite and quartz diorite composition and 10cm to 2m in length, are enclosed in the granodiorites, preferentially in the central part. The former may show either gradual or sharp contacts with the host granodiorite. Most of these enclaves show chilled margins. They may represent mingling between coeval mafic and felsic magmas. The intrusive rocks are cut by a few porphyritic microgranite, microgranodiorite and aplitic dikes. The dikes generally show subhorizontal orientations, although sometimes they clearly cross cut each other. They range in thickness from a few cm to 1m.

### Feshark

The Feshark intrusion is situated in the South of Ardestan (Fig. 1). Its coordinates are 32°50'–32°53'N and 52°21'–52°26'E. It is composed mainly of granodiorite, granite, diorite, and quartz-diorite. Quartz-diorite and diorites are dark grey and abundant in the western part of the intrusion. Granodiorite and granites are typically white to light grey and change gradually into granite, whereas they show a distinct boundary with quartz-diorite and diorites. Because of the occurrence of veins of granitic material in the dioritic rocks, we infer that diorites might have formed at the earlier stage. Granodiorites contain abundant rounded to ellipsoidal mafic microgranular enclaves of diorite and quartz diorite composition. They are 5–50cm in diameter and show chilled margins. Country rocks are Cretaceous and Eocene deposits. Submarine Cretaceous to Eocene deposits are mainly volcanic and volcano-sedimentary rocks, intercalated between deep sea sediments. Volcanic rocks include rhyolite, rhyodacite, trachyandesitic, andesite, and basalt. In the West, sedimentary rocks include *Inoceramus*-bearing limestones with silty marls and sandy limestones, which are metamorphosed near the intrusion contacts. The grade of metamorphism is locally high, from pyroxene hornfels to hornblende hornfels facies, especially along the margin of the western zones of the studied intrusion.

### ANALYTICAL TECHNIQUES

Sixty representative samples from the Kuh-e Dom, Mehrabad, Nasrand, Zafarghand, and Feshark were collected on the basis of their mineralogy, freshness, and geographic distribution. The selected samples were analyzed for major and trace elements. Major elements were analyzed by X-ray fluorescence (XRF) (Rigaku RIX 2000 with a Rh end window tube) using fused glass disks at Naruto University in Japan. Glass beads from finely grounded samples were prepared with a sample-to-flux ( $\text{Li}_2\text{B}_4\text{O}_7$ ) ratio of 1:10 and analyzed for major elements using fundamental parameter method spectrometry with analytical errors <1%.

Six representative samples for U-Pb zircon dating were collected from the Kuh-e Dom (granodiorite and diorite), Mehrabad (granodiorite), Nasrand (granodiorite), Zafarghand (granodiorite), and Feshark (granodiorite) intrusions. The samples were 3–7kg in weight. Whole rock samples were crushed using jaw crushers. The crushed samples were then sieved to obtain the size fraction above 53 mesh (~300µm). All samples were washed with water to remove dust. After washing and drying, magnetic minerals, such as magnetite, were removed with a Franz magnetic separator. More than 100 zircon grains were separated

from the samples by using standard mineral-separation techniques at University of Tehran, specifically heavy liquid (bromoform and methylene iodide), and finally purified by handpicking under a binocular microscope.

Zircon separates were mounted by using epoxy resin and polished. Prior to age determination, all zircon grains were investigated by cathodoluminescence (CL) to highlight zoning and possible inherited cores. U-Pb isotopic analyses of zircon were conducted by laser ablation inductively coupled plasma-mass spectrometry (LA ICP-MS) at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan (see Simonetti *et al.*, 2006). Detailed operating conditions for the LA system and the ICP-MS instrument and data reduction were the same described by Liu *et al.* (2008, 2010a, 2010b).

Zircon 91500 was used as external standard for U-Pb dating, and was analyzed twice every five analyses. Time-dependent drifts of U-Th-Pb isotopic ratios were corrected using a linear interpolation (with time) for every five analyses according to the variations of zircon 91500 (*i.e.* 2 zircon 91500 + 5 samples + 2 zircon 91500) (Liu *et al.*, 2010a). Preferred U-Th-Pb isotopic ratios used for zircon 91500 were from Wiedenbeck *et al.* (1995). Uncertainty of preferred values for the external standard zircon 91500 was propagated to the ultimate results of the samples. Concordia diagrams and weighted mean calculations were made using Isoplot/Ex\_ver3 (Ludwig, 2003).

## PETROGRAPHY

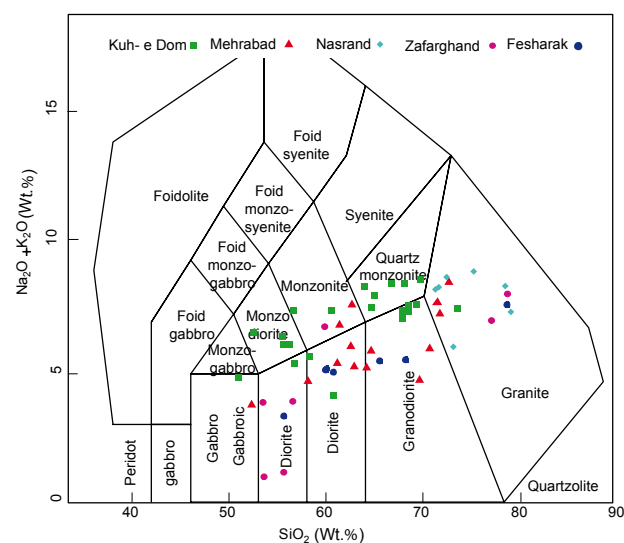
Felsic rocks in the Kuh-e Dom, Mehrabad, Nasrand, Zafarghand, and Feshark intrusions, are mostly granular, medium grained and composed mainly of quartz, K-feldspar, plagioclase, biotite, and hornblende, with small amounts of accessory minerals, including zircon, apatite, titanite, as well as opaque minerals, such as magnetite, hematite, pyrite, and chalcopyrite. Quartz and K-feldspar are typically anhedral and occur as interstitial phases. Occasionally, K-feldspar phenocrysts are present as large, irregular, poikilitic patches. They enclose fine-grained plagioclase, hornblende, biotite, and accessory minerals. Plagioclase occurs as euhedral to subhedral crystals with zoning or polysynthetic twinning. Plagioclase tends to be an early, dominant phase. Green hornblende and brown biotite are common mafic minerals and form euhedral to subhedral prisms of variable size.

The mafic-intermediate rocks in these intrusions are granular and medium grained; they contain more mafic minerals and plagioclase, and less quartz and K-feldspar compared to the granodiorite rocks. Quartz

and orthoclase are present in variable proportions. Both minerals are commonly late interstitial phases. Plagioclase occurs as euhedral to subhedral crystals, commonly with polysynthetic twinning and normal and oscillatory zoning. Hornblende and biotite are the most common mafic minerals, whereas in the mafic units orthopyroxene occurs as rare grains in the Kuh-e Dom and Zafarghand intrusions and forms euhedral to anhedral crystals and usually contains small inclusions of plagioclase. Apatite, titanite, and opaque minerals (mostly titanomagnetite, hematite, pyrite, and chalcopyrite) appear as accessory phases.

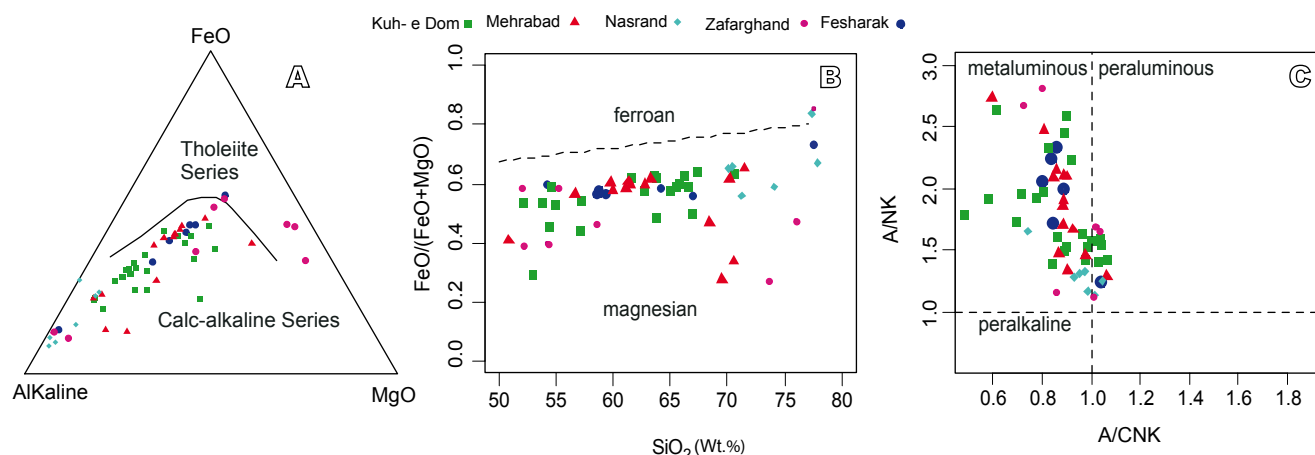
## GEOCHEMICAL COMPOSITION

Whole-rock analyses of major and trace elements of all samples are reported in Table I (Electronic Appendix, available at [www.geologica-acta.com](http://www.geologica-acta.com)). We use the classification diagram of Middlemost (1994) for characterizing the rock types. The samples plot in the fields of gabbro to granite (Fig. 2). The majority of the samples are subalkaline in nature and display a calc-alkaline trend (Irvine and Baragar, 1971; Fig. 3A). In the FeO/(FeO+MgO) vs. SiO<sub>2</sub> diagram (Frost *et al.*, 2001), all samples plot in the magnesium field (Fig. 3B). The A/CNK [Al<sub>2</sub>O<sub>3</sub>/(CaO+Na<sub>2</sub>O+K<sub>2</sub>O) molecular ratio, or Aluminum Saturation Index (ASI)] values of Shand (1943), are the most useful chemical discriminant between metaluminous (ASI<1) and peraluminous (ASI>1) intrusive rocks; the vast majority of the studied intrusion are metaluminous to slightly peraluminous (Fig. 3C). The least-evolved members are predominantly metaluminous, although some more evolved samples exhibit slightly peraluminous signatures with A/CNK ratios ranging from 1.0 to 1.1. The



**FIGURE 2.** Silica vs. alkali diagram (Middlemost, 1994), showing the studied samples plotted in the fields from granite to gabbro.





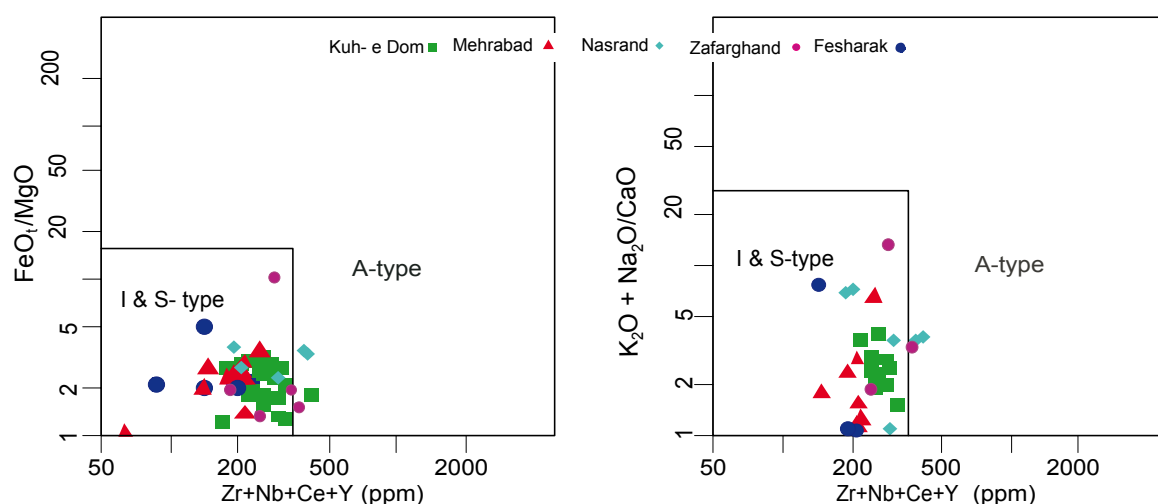
**FIGURE 3.** A) Alkaline ternary diagram ( $\text{Na}_2\text{O}+\text{K}_2\text{O}-\text{FeO}-\text{MgO}$ ; wt. %). Line separating the tholeiitic and calc-alkaline fields is from Irvine and Baragar (1971), B)  $\text{SiO}_2$  vs.  $\text{Fe}/(\text{FeO}+\text{MgO})$  diagram (Frost *et al.*, 2001), and C)  $[\text{Al}_2\text{O}_3]/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ mol vs.  $[\text{Al}_2\text{O}_3]/(\text{K}_2\text{O}+\text{Na}_2\text{O})$ mol diagram (Shand, 1943) for the granites of the Ardestan area.

ASI value of the studied samples is less than 1.1, which is associated mainly with I-type granites (Chappell and White, 1974; Chappell, 1999). Low ASI is consistent with the mafic mineral assemblage of amphibole±pyroxene±biotite in the studied samples (Chappell and White, 1974; White and Chappell, 1988). The peraluminous nature of a few samples may be attributed to hornblende differentiation (Zen, 1986) or heterogeneity of water content in the protolith (Waight *et al.*, 1998).

A discrimination plot of  $\text{Zr}+\text{Ce}+\text{Y}+\text{Nb}$  vs.  $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{CaO}$  and  $\text{FeO}_t/\text{MgO}$  (Whalen *et al.*, 1987) shows that the studied samples plot within the field of I- and S-type intrusive rocks and are distinct from the A-type granites of alkali nature (Fig. 4). The sharply linear negative trend between  $\text{P}_2\text{O}_5$  and  $\text{SiO}_2$  (Chappell, 1999) and sharply linear positive trend between Th and  $\text{SiO}_2$  from the most mafic to

the most felsic compositions (Chappell *et al.*, 1998) can be considered typical of I-type granite (Fig. 5). The oxidized I-type geochemical signatures of these intrusive rocks are also supported by their mineralogy, *i.e.* predominance of biotite and hornblende as mafic silicates, and the abundance of euhedral titanite and magnetite as accessory phases (Chappell and White, 1974). Lack of muscovite and monazite minerals is typical of I-type intrusive rocks. Apatite inclusions are common in biotite and hornblende, as are expected for I-type intrusive rocks and occur in larger individual crystals in the S-type varieties. The wide range of modal distribution from gabbro to granite, indicates the studied samples are I-type granitoids.

In the Mid Oceanic Ridge Basalt (MORB) normalized trace-element spider diagrams (Pearce, 1983), the five groups of intrusive rocks have similar trace-element patterns



**FIGURE 4.**  $\text{Zr}+\text{Ce}+\text{Y}+\text{Nb}$  vs.  $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{CaO}$  and  $\text{FeO}_t/\text{MgO}$  discrimination diagrams of Whalen *et al.* (1987).

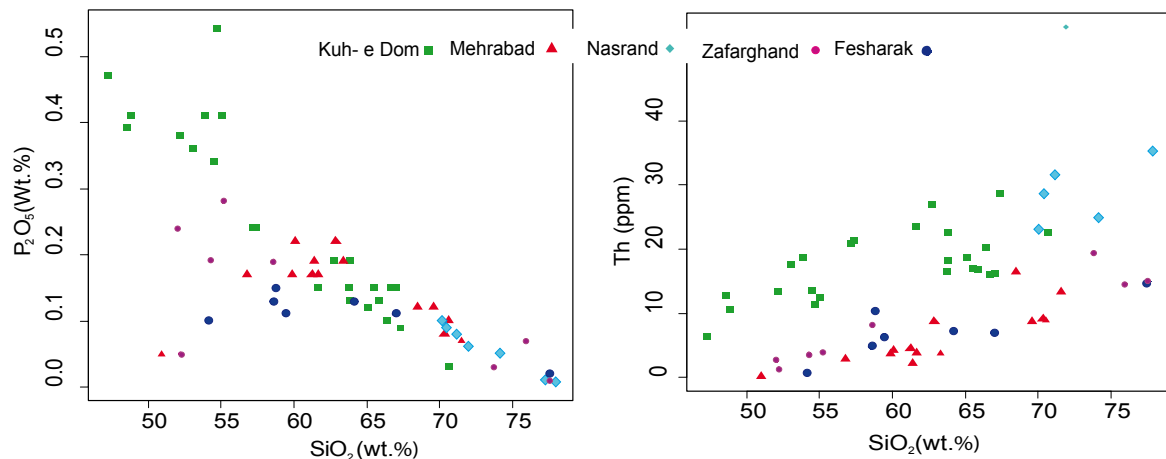


FIGURE 5.  $\text{SiO}_2$  vs.  $\text{P}_2\text{O}_5$  and Th diagrams indicating typical trends of I-type granite.

(Fig. 6). These rocks are enriched in Large Ion Lithophile Elements (LILEs: Cs, Rb, Ba, and K) and strongly depleted in High Field Strength Elements (HFSEs: Nb and Ti). These features are typical of subduction-related magmas (Gill, 1981; Pearce, 1983; Wilson, 1989). Strong depletion in Nb and Ti relative to other HFSE has been explained in terms of: i) retention of Nb-Ti-bearing refractory phases (*i.e.* rutile, titanite, amphibole) at the site of partial melting (*e.g.* Briquieu *et al.*, 1984); ii) melting of Nb-Ti-depleted source material, be it continental crust, island arc, or continental margin volcanic rocks; iii) recycling of ancient crustal material back into the mantle sources of magmas (*e.g.* Hergt *et al.*, 1989; Sage *et al.*, 1996); iv) metasomatized mantle wedge of volcanic arcs (Taylor and McLennan, 1985); and v) advanced fractional crystallization of Nb-Ti-bearing phases (ilmenite, titanite, etc.), while the negative P anomalies should result from apatite fractionation. In the Rb versus Y + Nb diagram (Pearce *et al.*, 1984; Fig. 7), all the samples display geochemical characteristics typical of I-type magmas, formed in a volcanic arc setting, due to their relatively low values of Nb and Y (see Aliashrafzadeh, 2013; Ghahramani, 2013; Hamzehie, 2013).

### ZIRCON U-Pb AGE DETERMINATION

One diorite sample from Kuh-e Dom (DK), and five granodiorite samples from Kuh-e Dom (GK), Mehrabad (MH), Nasrand (NS), Zafarghand (ZF), and Feshark (FS) were selected for zircon U-Pb geochronology (see U-Pb data in Table II). Zircon is a common accessory mineral in the studied rocks and forms prismatic crystals with a maximum size close to 300  $\mu\text{m}$ . The zircon crystals are automorphic to sub-idiomorphic, and display a well-developed oscillatory zoning indicative of growth under magmatic conditions (Koschek, 1993; Gao *et al.*, 2007). Zircon is a reliable recorder of magmatic conditions in

which it grew, because of its resistance to isotopic resetting at magmatic conditions and its ubiquitous presence in silicic magmas. In a few samples the occurrence of xenocrystic cores can be observed. To determine the age of emplacement of the granites in these samples, analyses were mostly carried out on the external domains of the zircons grains with magmatic textures.

Zircon grains have variable Th and U concentrations (Table II). Generally, a zircon with a Th/U ratio larger than 0.5 and positive correlation between Th and U is regarded as being derived from magmatic crystallization, while if the ratio is less than 0.1 it can be interpreted as metamorphic in origin (Belousova *et al.*, 2002). In this study, their Th/U ratios (Table II) are interpreted as being representative of magmatic zircon. This interpretation is supported by the zircon shapes and textures; and by the positive correlation between Th and U (Fig. 8), that indicate a magmatic origin for these zircons (Hoskin and Black, 2000; Belousova *et al.*, 2002; Xie *et al.*, 2006).

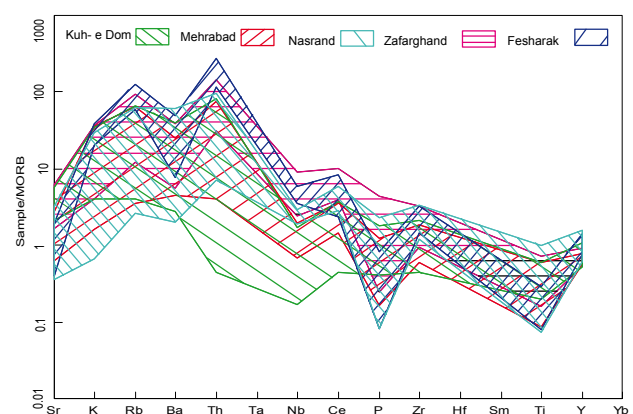
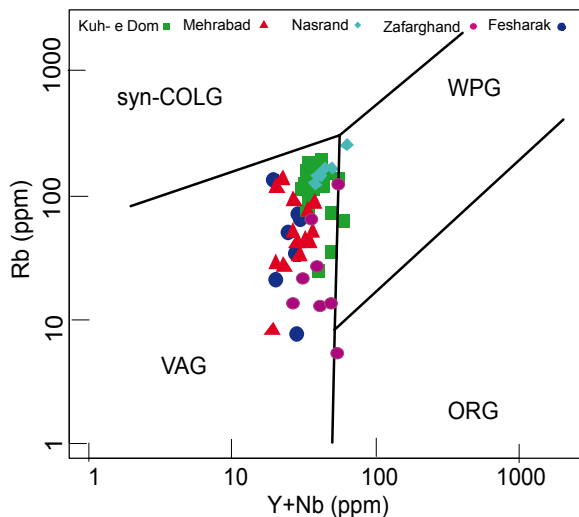


FIGURE 6. MORB-normalized trace patterns for the studied samples (values from Pearce, 1983).





**FIGURE 7.** Trace-element geotectonic discrimination diagram (Pearce *et al.*, 1984) for the studied granites. The granites plot in the volcanic arc granite field.

The results of calculating the isotopic age of the Kuh-e Dom granodiorite (GK), Kuh-e Dom diorite (DK), Mehrabad granodiorite (MH), Nasrand granodiorite (NS), Zafarghand granodiorite (ZF), and Feshark granodiorite (FS) are presented as concordia and average age graphics (Fig. 9) and the results are given in Table III. Therefore, the U-Pb zircon ages indicate that the Kuh-e Dom diorite and granodiorite were formed during the early to middle Eocene (Ypersian), the Mehrabad and Nasrand granodiorite during the late Eocene (Priabonian), the Zafarghand granodiorite during the late Oligocene (Chattian), and the Feshark granodiorite during the early Miocene (Burdigalian). Therefore, the plutonic rocks in the Ardestan magmatic segment reveal three main episodes of plutonic activity in the early-middle-late Eocene, late Oligocene, and early Miocene.

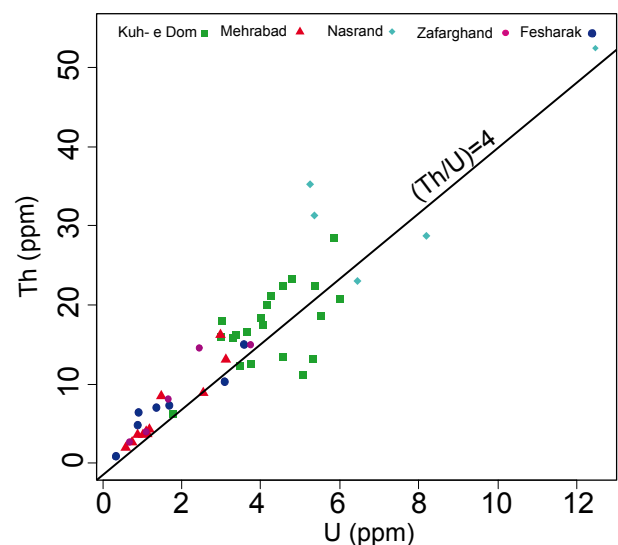
## DISCUSSION

This study reports zircon LA ICP-MS U-Pb ages for the Ardestan intrusive rocks, emplaced in the central part of the UDMA. It is generally believed that the UDMA was overlying the subducting slab of the Neo-Tethyan oceanic lithosphere beneath the Iranian Plate (Berberian and King, 1981; Mohajjel *et al.*, 2003; Agard *et al.*, 2005). Geochemical studies indicate that these intrusions are oxidized I-type, metaluminous to slightly peraluminous, commonly attributed to the magnesian series of calc-alkaline nature, and formed in a subduction-related setting, in accordance with the geological history of this area and in good agreement with other UDMA signatures.

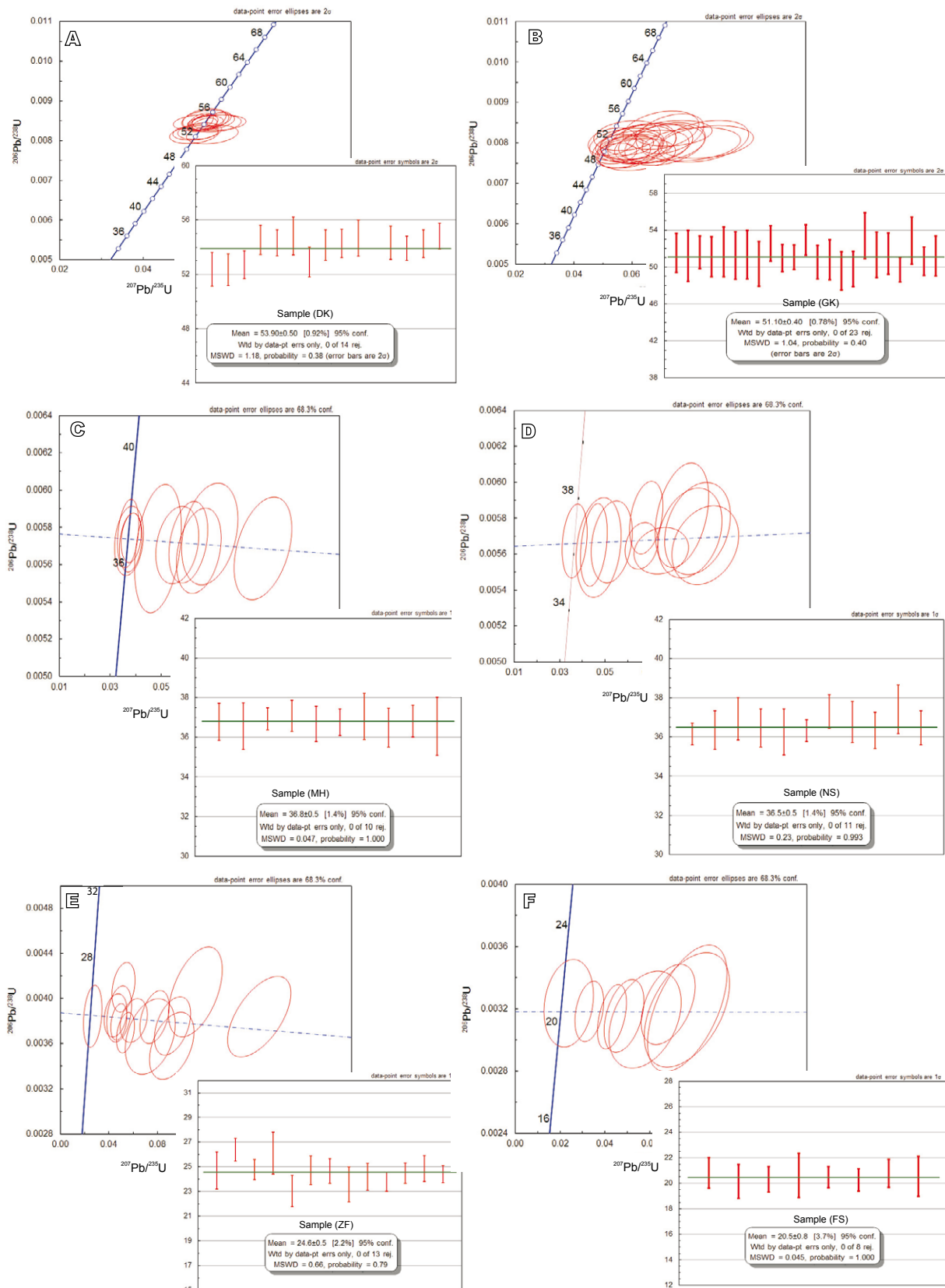
According to our U-Pb results, the granodiorite and diorite of the Kuh-e Dom intrusion were emplaced at 51–54Ma, during the early-middle Eocene, which is slightly older than previous dating by K-Ar (Technoexport, 1981), which yielded late Eocene ages. According to field observations, the intrusive rocks of Mehrabad, Nasrand, Zafarghand, and Feshark, in the Ardestan area, are intruded into early Eocene volcanic rocks (andesite, dacite latite, and tuffs), thus indicating a post-early Eocene age, in agreement with an Oligo-Miocene age estimated earlier (*e.g.* Aghanabati, 2004). The new isotopic data provide a revised age for these intrusive rocks, from the late Eocene (Mehrabad and Nasrand), in contrast with the earlier views, to late Oligocene (Zafarghand), to early Miocene (Feshark). Therefore, the Tertiary plutonism in the Ardestan area can be divided into three main episodes; i) early-middle-late Eocene, ii) late Oligocene and iii) early Miocene intrusions, which have been considered central part of the UDMA plutonism. The intrusive rocks in the Ardestan area were emplaced from early Eocene to early Miocene plutonic interval and the Zafarghand and Feshark intrusive rocks, which are closer to the trench, are the younger intrusive units in the Ardestan area. It is apparent that the plutonism was more intense during the Eocene for the central part of the UDMA belt, as shown also by Berberian and Berberian (1981).

The geochronologic data of the intrusive rocks studied here were compared with those available of plutonic rocks elsewhere in the UDMA. The overall data are listed in Table IV.

Chiu *et al.* (2013) suggested that magmatism in the UDMA was most active and widespread in the Eocene and



**FIGURE 8.** The positive correlation between Th and U, indicating a magma origin of zircons.



**FIGURE 9.** Concordia diagrams displaying U-Pb data from A) the Kuh-e Dom diorite, B) Kuh-e Dom granodiorite, C) Mehrabad granodiorite, D) Nasrand granodiorite, E) Zafarghand granodiorite and F) Feshark granodiorite.

Oligocene, and magmatic activity lasting from ca. 21 to 6Ma ending with small-volume intrusions. Cessation of arc magmatism took place progressively from the Northwest to the southeast. This southeastward termination of the UDMA magmatism is consistent with the notion of oblique and thus diachronous collision between Arabia and Eurasia, with the collision initiating in the Northwest and propagating progressively to the Southeast along the Zagros suture zone (see Chiu *et al.*, 2013).

From a geochronological point of view, the Ardestan intrusive rocks are broadly similar to the other intrusive rocks in the UDMA spanning from 81.0 to 5.4Ma. This semi-continuously activity all along the UDMA can be related to the persistent subduction of the Neo-Tethys oceanic crust below the Iranian plate. The Kuh-e Dom, Mehrabad, Nasrand, and Zafarghand were emplaced during the Eocene-Oligocene epoch during the maximum magmatic activity. Another phase of plutonism in the Ardestan area was responsible for the emplacement of the Feshark intrusive rocks. Considering most of the researchers agree that the timing of the continental closure is Miocene (*e.g.* Dewey and Sengör, 1979; Robertson, 2000; McQuarrie *et al.*, 2003; Mohajjel *et al.*, 2003; Homke *et al.*, 2004; Guest *et al.*, 2006; Omrani *et al.*, 2008; Ao *et al.*, 2016). It seems that the Eocene-Oligocene intrusive rocks (*i.e.* Kuh-e Dom, Mehrabad, Nasrand, and Zafarghand) in the Ardestan area were emplaced prior to the collision, showing a pre-collisional volcanic arc setting, and that the younger intrusion (*e.g.* Feshark) was formed relatively late in the subduction history and may represent post-collisional plutonism.

## CONCLUSIONS

The petrological, geochemical, and geochronological study of the Ardestan intrusive rocks reveals important clues to decipher the complex magmatic processes in the central section of the Urumieh-Dokhtar magmatic arc belt. All magmatic phases forming the intrusive rocks of the Ardestan area were metaluminous to slightly peraluminous, typical of I-type granites and belong to magnesian series of calc-alkaline nature and display the geochemical characteristics typical of oxidized I-type volcanic arc granitoids.

The LA ICP-MS U-Pb zircon geochronology of the Ardestan plutonic rocks documents two major intrusive phases. An Eocene-Oligocene subduction-related magmatism formed the Kuh-e Dom, Mehrabad, Nasrand, and Zafarghand intrusive rocks. The youngest lower Miocene Feshark intrusion probably represents post-collision magmatism within the central part of the UDMA belt.

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## ELECTRONIC APPENDIX I

**TABLE I.** Major and trace elements data from the Ardestan area (GK: Kuh-e Dom granodiorite, DK: Kuh-e Dom diorite, MH: Mehrabad granodiorite, NS: Nasrand granodiorite, ZF: Zafarghand granodiorite, FS: Feshark granodiorite) (Some of the data of Hamzehie, 2013; Ghahramani, 2013; Aliashrafzadeh, 2013)

| Sample                         | GK1   | GK2   | GK3   | GK4   | GK5   | GK6   | GK7   | GK8   | GK9   | GK10  | GK11  | GK12  |
|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Wt. %                          |       |       |       |       |       |       |       |       |       |       |       |       |
| SiO <sub>2</sub>               | 63.7  | 65    | 66.3  | 65.8  | 66.91 | 65.43 | 67.3  | 63.77 | 62.68 | 66.59 | 70.6  | 63.8  |
| TiO <sub>2</sub>               | 0.48  | 0.43  | 0.4   | 0.44  | 0.5   | 0.48  | 0.32  | 0.55  | 0.61  | 0.47  | 0.24  | 0.46  |
| Al <sub>2</sub> O <sub>3</sub> | 14.95 | 15.05 | 15.25 | 15.25 | 15.69 | 16    | 15.7  | 16.38 | 16.15 | 15.76 | 13.85 | 16    |
| Fe <sub>2</sub> O <sub>3</sub> | 1.79  | 1.79  | 1.67  | 1.78  | 1.24  | 2.17  | 1.47  | 2.22  | 2.51  | 1.94  | 1.14  | 1.38  |
| FeO                            | 2.38  | 2.28  | 2.02  | 2.17  | 1.34  | 2.37  | 1.59  | 2.58  | 2.83  | 2.36  | 1.37  | 1.83  |
| MnO                            | 0.09  | 0.07  | 0.07  | 0.11  | 0.06  | 0.09  | 0.04  | 0.08  | 0.08  | 0.06  | 0.03  | 0.09  |
| MgO                            | 1.44  | 1.68  | 1.22  | 1.43  | 1.36  | 1.65  | 0.9   | 1.59  | 2.11  | 1.68  | 0.79  | 1.97  |
| CaO                            | 3.61  | 2.84  | 2.66  | 3.12  | 4.11  | 2.91  | 2.12  | 4.28  | 4.13  | 3.26  | 2.01  | 3.08  |
| Na <sub>2</sub> O              | 3.11  | 3.16  | 3.22  | 3.33  | 3.85  | 3.76  | 3.28  | 3.53  | 3.23  | 3.62  | 3.37  | 5     |
| K <sub>2</sub> O               | 3.72  | 3.98  | 4.28  | 4.15  | 4.64  | 4.71  | 5.23  | 4.52  | 5.13  | 3.81  | 3.98  | 1.8   |
| P <sub>2</sub> O <sub>5</sub>  | 0.15  | 0.12  | 0.1   | 0.13  | 0.15  | 0.15  | 0.09  | 0.19  | 0.19  | 0.15  | 0.03  | 0.13  |
| Total                          | 95.42 | 96.40 | 97.19 | 97.71 | 99.85 | 99.72 | 98.04 | 99.69 | 99.65 | 99.70 | 97.41 | 95.54 |
| ppm                            |       |       |       |       |       |       |       |       |       |       |       |       |
| Ce                             | 56.3  | 100   | 65.8  | 56.6  | 45.5  | 39.4  | 61.4  | 47.3  | 55.6  | 46    | 65    | 46    |
| Cr                             | 60    | 70    | 50    | 40    | 10    | 0     | 10    | 20    | 16.6  | 10    | 10    | 10    |
| Nb                             | 14.7  | 14.5  | 15.1  | 13.9  | 15    | 12.93 | 19.9  | 17.2  | 16.16 | 13.9  | 14.5  | 14.8  |
| Ni                             | 5     | 5     | 4     | 4     | 6     | 4     | 5     | 9     | 9.1   | 6     | 8     | 8     |
| Pb                             | 11    | 12    | 11    | 10    | 8     | 10.1  | 10    | 12    | 9.1   | 10    | 14    | *     |
| Rb                             | 122.5 | 146   | 154.5 | 122.5 | 117   | 156.8 | 147.5 | 146   | 185.5 | 111   | 143   | 73.2  |
| Sr                             | 263   | 295   | 249   | 247   | 354   | 279.1 | 197.5 | 395   | 340.4 | 276   | 218   | 312   |
| Th                             | 16.4  | 18.5  | 20.1  | 16.8  | 16.05 | 16.85 | 28.6  | 22.5  | 26.79 | 15.9  | 22.5  | 18.05 |
| Y                              | 17.8  | 19.3  | 17.2  | 17.7  | 18.5  | 22.7  | 17.9  | 19.1  | 25.3  | 16.2  | 18.4  | 18.2  |
| Zr                             | 164   | 160   | 186   | 160   | 180   | 171   | 161   | 171   | 187   | 179   | 125   | 182   |
| Ba                             | 560   | 685   | 569   | 534   | 648   | 526.5 | 519   | 589   | 498.3 | 577   | 567   | 290   |



TABLE I. Continued

| Sample                         | DK1   | DK2   | DK3   | DK4   | DK5   | DK6   | DK7   | DK8   | DK9   | DK10  | DK11  |
|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Wt. %                          |       |       |       |       |       |       |       |       |       |       |       |
| SiO <sub>2</sub>               | 57.1  | 57.3  | 54.96 | 48.79 | 48.5  | 54.6  | 47.2  | 54.4  | 61.6  | 53    | 53.8  |
| TiO <sub>2</sub>               | 0.75  | 0.79  | 1.01  | 1.07  | 0.98  | 1     | 1.02  | 0.86  | 0.57  | 0.94  | 1.03  |
| Al <sub>2</sub> O <sub>3</sub> | 16.5  | 16.15 | 19.19 | 17.72 | 19.75 | 19.5  | 17.6  | 16.4  | 15.9  | 16.85 | 17.1  |
| Fe <sub>2</sub> O <sub>3</sub> | 1.50  | 2.31  | 2.75  | 2.70  | 2.74  | 2.34  | 2.11  | 2.03  | 2.15  | 1.35  | 3.37  |
| FeO                            | 2.02  | 4.48  | 4.21  | 3.49  | 4.32  | 3.95  | 4.09  | 3.38  | 2.74  | 2.12  | 5.03  |
| MnO                            | 0.1   | 0.13  | 0.1   | 0.35  | 0.19  | 0.13  | 0.13  | 0.14  | 0.09  | 0.21  | 0.18  |
| MgO                            | 2.57  | 3.82  | 3.75  | 2.21  | 2.36  | 2.81  | 4.91  | 4.04  | 1.68  | 5.1   | 4.37  |
| CaO                            | 8     | 6.64  | 7     | 14.91 | 8.76  | 8     | 12.45 | 8.16  | 4.78  | 11.35 | 7.2   |
| Na <sub>2</sub> O              | 3.29  | 3.39  | 3.56  | 2.42  | 3.13  | 3.95  | 3.1   | 4.56  | 3.48  | 4.21  | 3.18  |
| K <sub>2</sub> O               | 3.83  | 0.61  | 2.55  | 5.52  | 3.09  | 1.34  | 1.48  | 0.83  | 3.85  | 1.77  | 3.2   |
| P <sub>2</sub> O <sub>5</sub>  | 0.24  | 0.24  | 0.41  | 0.41  | 0.39  | 0.54  | 0.47  | 0.34  | 0.15  | 0.36  | 0.41  |
| Total                          | 95.90 | 95.86 | 99.49 | 99.59 | 94.21 | 98.16 | 94.56 | 95.14 | 96.99 | 97.26 | 98.87 |
| ppm                            |       |       |       |       |       |       |       |       |       |       |       |
| Ce                             | 61.1  | 62.3  | 50.2  | 53.9  | 52.8  | 68.6  | 49.7  | 68.1  | 61.7  | 57.7  | 79.3  |
| Cr                             | 40    | 90    | 30    | 118.2 | 30    | 66    | 210   | 200   | 20    | 80    | 80    |
| Nb                             | 18.4  | 17.4  | 13.8  | 8.54  | 13.8  | 31.8  | 11.7  | 22.2  | 19.8  | 24.6  | 27.8  |
| Ni                             | 13    | 26    | 13    | 27.8  | 15    | 32    | 69    | 69    | 11    | 24    | 37    |
| Pb                             | 13    | 7     | 14    | 8.8   | 11    | 21    | 9     | 6     | 12    | *     | *     |
| Rb                             | 114.5 | 24    | 93.4  | 184.3 | 113.5 | 62.7  | 75.5  | 35.1  | 146   | 73.1  | 135.5 |
| Sr                             | 525   | 460   | 692   | 430.6 | 518   | 672   | 725   | 460   | 354   | 733   | 583   |
| Th                             | 20.8  | 21.2  | 12.35 | 10.49 | 12.7  | 11.35 | 6.27  | 13.5  | 23.4  | 17.6  | 18.65 |
| Y                              | 25.4  | 22.6  | 20.1  | 25.8  | 23.4  | 27.6  | 22.4  | 26.5  | 27.4  | 23.5  | 26.8  |
| Zr                             | 193   | 197   | 137   | 91.2  | 119   | 195   | 85    | 211   | 207   | 245   | 294   |
| Ba                             | 619   | 110.5 | 424   | 374.4 | 460   | 208   | 280   | 123   | 546   | 356   | 454   |

TABLE I. Continued

| Sample                         | MH1   | MH2   | MH3   | MH4   | MH5   | MH6   | MH7   | MH8   | MH9   | MH10  | MH11  | MH12  |
|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Wt.%                           |       |       |       |       |       |       |       |       |       |       |       |       |
| SiO <sub>2</sub>               | 59.79 | 56.69 | 61.56 | 63.30 | 61.31 | 68.4  | 70.21 | 69.50 | 71.46 | 50.89 | 59.97 | 61.13 |
| TiO <sub>2</sub>               | 0.71  | 0.85  | 0.75  | 0.72  | 0.67  | 0.47  | 0.33  | 0.44  | 0.3   | 0.73  | 0.89  | 0.72  |
| Al <sub>2</sub> O <sub>3</sub> | 16.59 | 16.63 | 15.81 | 15.74 | 15.68 | 15.56 | 14.67 | 15.89 | 14.27 | 15.93 | 15.94 | 15.87 |
| Fe <sub>2</sub> O <sub>3</sub> | 2.79  | 3.00  | 2.60  | 2.46  | 3.12  | 1.07  | 1.37  | 0.51  | 1.47  | 2.65  | 3.30  | 2.86  |
| FeO                            | 4.50  | 5.37  | 4.19  | 3.67  | 3.84  | 1.74  | 1.58  | 0.72  | 1.54  | 5.56  | 4.49  | 4.24  |
| MnO                            | 0.14  | 0.14  | 0.11  | 0.10  | 0.35  | 0.06  | 0.04  | 0.04  | 0.04  | 0.14  | 0.13  | 0.13  |
| MgO                            | 2.93  | 4.11  | 2.84  | 2.29  | 2.49  | 1.98  | 0.98  | 1.89  | 0.82  | 8.08  | 3.29  | 3     |
| CaO                            | 6.49  | 7.74  | 6.22  | 5.25  | 4.24  | 5.64  | 2.79  | 4.83  | 1.32  | 11.56 | 4.36  | 5.36  |
| Na <sub>2</sub> O              | 3.47  | 2.98  | 3.34  | 3.82  | 4.15  | 4.04  | 3.00  | 5.12  | 3.36  | 3.15  | 3.88  | 3.29  |
| K <sub>2</sub> O               | 1.88  | 1.68  | 1.92  | 2.03  | 3.5   | 0.71  | 4.74  | 0.86  | 5.17  | 0.6   | 2.96  | 2.72  |
| P <sub>2</sub> O <sub>5</sub>  | 0.17  | 0.17  | 0.17  | 0.19  | 0.19  | 0.12  | 0.08  | 0.12  | 0.07  | 0.05  | 0.22  | 0.17  |
| Total                          | 99.46 | 99.36 | 99.50 | 99.57 | 99.54 | 99.79 | 99.80 | 99.91 | 99.81 | 99.35 | 99.44 | 99.48 |
| ppm                            |       |       |       |       |       |       |       |       |       |       |       |       |
| Ce                             | 26.2  | 22.8  | 27.3  | 31.2  | 21.1  | 36    | 32    | 19.1  | 37.3  | 4.4   | 29    | 29.2  |
| Cr                             | 10    | 30    | 20    | 20    | 10    | 10    | 5     | 5     | 10    | 200   | 20    | 20    |
| Nb                             | 3.8   | 3.5   | 3.9   | 5.1   | 2.7   | 6     | 4.5   | 4.9   | 5.5   | 0.6   | 5.1   | 4     |
| Ni                             | 4.4   | 12.8  | 9.1   | 4.9   | 7.6   | 0.1   | 0.2   | 2.3   |       | 78.6  | 9     | 8.8   |
| Pb                             | 6.7   | 5.6   | 6.4   | 8.5   | 9.1   | 5.2   | 5.6   | 4.7   | 8.1   | 2     | 17.5  | 8.3   |
| Rb                             | 41    | 41    | 42.6  | 50.4  | 89.3  | 31.4  | 114.5 | 26.2  | 133   | 8     | 83.9  | 73.5  |
| Sr                             | 310   | 341   | 302   | 307   | 257   | 619   | 338   | 678   | 279   | 282   | 317   | 348   |
| Th                             | 3.59  | 2.78  | 3.79  | 3.72  | 2.09  | 16.4  | 9.08  | 8.72  | 13.25 | 0.09  | 4.14  | 4.45  |
| Y                              | 30.6  | 24.9  | 28.3  | 31.4  | 24.1  | 23.5  | 15.8  | 17.9  | 17    | 18.4  | 32.1  | 29.7  |
| Zr                             | 130   | 90    | 140   | 140   | 100   | 150   | 160   | 180   | 190   | 40    | 150   | 150   |
| Ba                             | 419   | 347   | 428   | 466   | 751   | 150.5 | 765   | 250   | 783   | 55.9  | 695   | 588   |

TABLE I. Continued

| Sample                         | MH13  | MH14  | NS1   | NS2   | NS3   | NS4   | NS5   | NS6   | ZF1   | ZF2   | ZF3   | ZF4   |
|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Wt. %                          |       |       |       |       |       |       |       |       |       |       |       |       |
| SiO <sub>2</sub>               | 70.55 | 62.78 | 70.42 | 74.07 | 77.88 | 71.89 | 71.22 | 70.08 | 77.56 | 55.15 | 58.61 | 75.93 |
| TiO <sub>2</sub>               | 0.4   | 0.77  | 0.36  | 0.27  | 0.16  | 0.28  | 0.34  | 0.43  | 0.11  | 1.18  | 0.88  | 0.33  |
| Al <sub>2</sub> O <sub>3</sub> | 15.38 | 16.06 | 14.31 | 13.92 | 12.53 | 13.46 | 14.64 | 14.52 | 12.14 | 17.1  | 16.38 | 13.01 |
| Fe <sub>2</sub> O <sub>3</sub> | 0.66  | 2.35  | 1.49  | 0.53  | 0.34  | 1.08  | 0.87  | 1.54  | 0.61  | 2.94  | 3.22  | 0.41  |
| FeO                            | 0.79  | 3.77  | 1.60  | 0.52  | 0.39  | 1.49  | 0.89  | 1.68  | 0.64  | 5.87  | 4.45  | 0.49  |
| MnO                            | 0.06  | 0.11  | 0.05  | 0.03  | 0.02  | 0.04  | 0.03  | 0.07  | 0.02  | 0.23  | 0.2   | 0.02  |
| MgO                            | 1.55  | 2.55  | 0.83  | 0.36  | 0.19  | 0.03  | 0.7   | 0.91  | 0.11  | 4.14  | 5.18  | 0.55  |
| CaO                            | 3.09  | 5.73  | 2.31  | 1.23  | 1.08  | 5.48  | 2.39  | 2.21  | 0.62  | 8.56  | 3.56  | 2.13  |
| Na <sub>2</sub> O              | 6.41  | 3.58  | 3.38  | 4.03  | 3.64  | 2.97  | 3.55  | 3.74  | 3.72  | 3.33  | 4.21  | 6.75  |
| K <sub>2</sub> O               | 0.92  | 1.64  | 4.97  | 4.94  | 3.74  | 3.04  | 5.18  | 4.5   | 4.39  | 0.55  | 2.57  | 0.24  |
| P <sub>2</sub> O <sub>5</sub>  | 0.1   | 0.22  | 0.09  | 0.05  | 0.01  | 0.06  | 0.08  | 0.1   | 0.01  | 0.28  | 0.19  | 0.07  |
| Total                          | 99.90 | 99.56 | 99.80 | 99.95 | 99.98 | 99.82 | 99.89 | 99.78 | 99.93 | 99.33 | 99.45 | 99.93 |
| ppm                            |       |       |       |       |       |       |       |       |       |       |       |       |
| Ce                             | 27.2  | 31.6  | 80.8  | 25    | 23.4  | 82.2  | 52.7  | 72.3  | 58.9  | 43.8  | 46.3  | 41.4  |
| Cr                             | *     | *     | 10    | *     | 8     | 10    | 10    | 10    | 10    | 50    | 20    | 10    |
| Nb                             | 3.8   | 4.3   | 14.3  | 12.3  | 15.5  | 20.4  | 14.6  | 16.3  | 9.8   | 9.6   | 8.9   | 9.8   |
| Ni                             | 1.1   | 3     | *     | *     | *     | *     | *     | *     | *     | 25.7  | 8.1   | 2.4   |
| Pb                             | 7     | 6.4   | 8.7   | 3.7   | 3.3   | 6.7   | 6.4   | 9.3   | 8.1   | 6.2   | 5.4   | 1.4   |
| Rb                             | 27.2  | 50.5  | 161   | 139.4 | 119.5 | 253   | 148   | 165   | 123.5 | 13.5  | 64.2  | 5.2   |
| Sr                             | 483.7 | 439.6 | 194   | 172.3 | 178   | 47.5  | 234   | 194   | 43.2  | 348   | 252   | 161.5 |
| Th                             | 8.9   | 8.7   | 28.9  | 25    | 35.3  | 54.6  | 31.4  | 23.2  | 15    | 3.96  | 8.04  | 14.55 |
| Y                              | 16.3  | 22.3  | 29.1  | 27.7  | 23    | 42.3  | 25.9  | 32.8  | 45.1  | 37.7  | 25.4  | 46.7  |
| Zr                             | 146.7 | 122.6 | 260   | 139.3 | 130   | 150   | 210   | 290   | 170   | 240   | 160   | 270   |
| Ba                             | 132.4 | 283.3 | 822   | 715.9 | 666   | 151.5 | 986   | 808   | 1215  | 404   | 610   | 40.6  |

TABLE I. Continued

| Sample                         | ZF5   | ZF6   | ZF7   | ZF8   | FS1   | FS2   | FS3   | FS4   | FS5   | FS6   | FS7   |
|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Wt. %                          |       |       |       |       |       |       |       |       |       |       |       |
| SiO <sub>2</sub>               | 52.01 | 54.29 | 73.72 | 52.25 | 64.19 | 66.95 | 58.74 | 54.17 | 77.53 | 58.58 | 59.43 |
| TiO <sub>2</sub>               | 1.51  | 1.26  | 0.55  | 1.04  | 0.68  | 0.6   | 0.8   | 0.91  | 0.13  | 0.81  | 0.75  |
| Al <sub>2</sub> O <sub>3</sub> | 15.79 | 17.94 | 13.52 | 16.55 | 15.48 | 15.3  | 16.66 | 17.08 | 11.98 | 16.19 | 17.29 |
| Fe <sub>2</sub> O <sub>3</sub> | 3.70  | 3.02  | 0.88  | 3.14  | 2.24  | 1.62  | 2.81  | 3.23  | 0.61  | 2.92  | 2.45  |
| FeO                            | 7.59  | 5.66  | 1.27  | 5.72  | 3.47  | 2.45  | 4.69  | 6.99  | 0.67  | 4.91  | 4.13  |
| MnO                            | 0.17  | 3.53  | 0.81  | 6.21  | 0.1   | 0.05  | 0.13  | 0.19  | 0.02  | 0.1   | 0.11  |
| MgO                            | 5.34  | 8.66  | 3.46  | 9.24  | 2.45  | 1.94  | 3.4   | 4.7   | 0.25  | 3.75  | 3.14  |
| CaO                            | 8.93  | 3.64  | 5.18  | 4.25  | 5.42  | 5.19  | 6.93  | 8.49  | 1.05  | 6.93  | 7.08  |
| Na <sub>2</sub> O              | 3.13  | 0.79  | 0.35  | 0.54  | 3.33  | 5.25  | 3.36  | 2.75  | 2.41  | 4.17  | 3.51  |
| K <sub>2</sub> O               | 0.71  | 0.35  | 0.1   | 0.35  | 2.11  | 0.24  | 1.77  | 0.56  | 5.25  | 0.92  | 1.51  |
| P <sub>2</sub> O <sub>5</sub>  | 0.24  | 0.19  | 0.03  | 0.05  | 0.13  | 0.11  | 0.15  | 0.1   | 0.02  | 0.13  | 0.11  |
| Total                          | 99.12 | 99.33 | 99.87 | 99.33 | 99.60 | 99.71 | 99.44 | 99.18 | 99.92 | 99.41 | 99.51 |
| ppm                            |       |       |       |       |       |       |       |       |       |       |       |
| Ce                             | 28.6  | 34.1  | 48.8  | 39.3  | 35    | 29.1  | 36.6  | 14.6  | 24.7  | 32.6  | 28    |
| Cr                             | 70    | 20.8  | *     | 138   | 3.7   | *     | 4.5   | 2.5   | *     | 9.9   | 11.5  |
| Nb                             | 6.7   | 7.1   | 10.3  | 7.7   | 6.9   | 6.2   | 6.6   | 2.4   | 2.7   | 5.1   | 4.8   |
| Ni                             | 47.5  | 11.9  | 1.9   | 54.9  | 4.1   | 2.1   | 4.6   | 2.7   | *     | 5.3   | 2.9   |
| Pb                             | 4     | 19.5  | 2.2   | 1.7   | 7.9   | 4.5   | 8.1   | 7.4   | 9.2   | 4.7   | 5.1   |
| Rb                             | 25.8  | 20.3  | 12.4  | 13    | 69.9  | 7.1   | 62.1  | 19.3  | 128.3 | 33.5  | 49.3  |
| Sr                             | 342   | 336.6 | 254.4 | 385.5 | 245.6 | 220.6 | 281.4 | 332.6 | 75.9  | 243.4 | 270.6 |
| Th                             | 2.67  | 3.7   | 19.3  | 1.4   | 7.3   | 7     | 10.4  | 0.8   | 14.9  | 4.8   | 6.4   |
| Y                              | 31.5  | 23.9  | 30.1  | 18.4  | 22.3  | 21.2  | 23.3  | 17.4  | 16.8  | 22.1  | 20    |
| Zr                             | 110   | 158.1 | 303.5 | 108.5 | 166.7 | 137   | 122.5 | 53.5  | 100.8 | 81.2  | 167.7 |
| Ba                             | 275   | 346.5 | 96.9  | 128.7 | 375.7 | 89.7  | 361.6 | 156.5 | 494.4 | 219.7 | 303.2 |

**TABLE II.** U-Th-Pb data for the intrusive rocks of Ardestan area. (GK: Kuh-e Dom granodiorite, DK: Kuh-e Dom diorite, MH: Mehrabad granodiorite, NS: Nasrand granodiorite, ZF: Zafarghand granodiorite, FS: Feshark granodiorite)

| Sample | Pb<br>ppm | Th <sup>232</sup><br>ppm | U <sup>238</sup><br>ppm | Th/U | <sup>207</sup> Pb/ <sup>206</sup> Pb<br>Ratio | <sup>207</sup> Pb/ <sup>206</sup> Pb<br>1sigma | <sup>207</sup> Pb/ <sup>235</sup> U<br>Ratio | <sup>207</sup> Pb/ <sup>235</sup> U<br>1sigma | <sup>206</sup> Pb/ <sup>238</sup> U<br>Ratio | <sup>206</sup> Pb/ <sup>238</sup> U<br>1sigma | rho    |
|--------|-----------|--------------------------|-------------------------|------|-----------------------------------------------|------------------------------------------------|----------------------------------------------|-----------------------------------------------|----------------------------------------------|-----------------------------------------------|--------|
| GK-01  | 4.13      | 258                      | 388                     | 0.67 | 0.0764                                        | 0.0054                                         | 0.0858                                       | 0.0066                                        | 0.0080                                       | 0.0002                                        | 0.2688 |
| GK-02  | 2.06      | 96.1                     | 221                     | 0.44 | 0.0718                                        | 0.0066                                         | 0.0714                                       | 0.0057                                        | 0.0080                                       | 0.0002                                        | 0.3410 |
| GK-03  | 4.70      | 304                      | 483                     | 0.63 | 0.0491                                        | 0.0033                                         | 0.0532                                       | 0.0034                                        | 0.0080                                       | 0.0001                                        | 0.2703 |
| GK-04  | 4.15      | 301                      | 431                     | 0.70 | 0.0534                                        | 0.0046                                         | 0.0582                                       | 0.0052                                        | 0.0080                                       | 0.0002                                        | 0.2341 |
| GK-05  | 1.95      | 99.1                     | 202                     | 0.49 | 0.0834                                        | 0.0073                                         | 0.0847                                       | 0.0064                                        | 0.0080                                       | 0.0002                                        | 0.3493 |
| GK-06  | 2.84      | 169                      | 311                     | 0.54 | 0.0591                                        | 0.0044                                         | 0.0634                                       | 0.0048                                        | 0.0080                                       | 0.0002                                        | 0.3364 |
| GK-07  | 2.29      | 104                      | 254                     | 0.41 | 0.0621                                        | 0.0066                                         | 0.0651                                       | 0.0065                                        | 0.0080                                       | 0.0002                                        | 0.2550 |
| GK-08  | 3.78      | 245                      | 401                     | 0.61 | 0.0573                                        | 0.0053                                         | 0.0585                                       | 0.0050                                        | 0.0078                                       | 0.0002                                        | 0.2832 |
| GK-09  | 4.39      | 296                      | 431                     | 0.69 | 0.0545                                        | 0.0049                                         | 0.0583                                       | 0.0047                                        | 0.0082                                       | 0.0002                                        | 0.2303 |
| GK-10  | 9.02      | 889                      | 840                     | 1.06 | 0.0509                                        | 0.0032                                         | 0.0556                                       | 0.0033                                        | 0.0079                                       | 0.0001                                        | 0.2398 |
| GK-11  | 11.71     | 971                      | 1126                    | 0.86 | 0.0540                                        | 0.0030                                         | 0.0594                                       | 0.0033                                        | 0.0080                                       | 0.0001                                        | 0.2321 |
| GK-12  | 8.82      | 767                      | 769                     | 1.00 | 0.0656                                        | 0.0049                                         | 0.0743                                       | 0.0055                                        | 0.0082                                       | 0.0001                                        | 0.2149 |
| GK-13  | 4.90      | 252                      | 514                     | 0.49 | 0.0578                                        | 0.0050                                         | 0.0602                                       | 0.0049                                        | 0.0079                                       | 0.0001                                        | 0.2193 |
| GK-14  | 3.01      | 142                      | 323                     | 0.44 | 0.0626                                        | 0.0050                                         | 0.0669                                       | 0.0053                                        | 0.0079                                       | 0.0002                                        | 0.2715 |
| GK-15  | 4.43      | 319                      | 460                     | 0.69 | 0.0591                                        | 0.0052                                         | 0.0617                                       | 0.0054                                        | 0.0077                                       | 0.0002                                        | 0.2374 |
| GK-16  | 5.83      | 409                      | 600                     | 0.68 | 0.0549                                        | 0.0040                                         | 0.0572                                       | 0.0038                                        | 0.0077                                       | 0.0001                                        | 0.2896 |
| GK-17  | 3.19      | 152                      | 320                     | 0.47 | 0.0619                                        | 0.0049                                         | 0.0700                                       | 0.0053                                        | 0.0083                                       | 0.0002                                        | 0.3059 |
| GK-18  | 2.72      | 134                      | 285                     | 0.47 | 0.0643                                        | 0.0055                                         | 0.0703                                       | 0.0061                                        | 0.0080                                       | 0.0002                                        | 0.2761 |
| GK-19  | 2.71      | 144                      | 307                     | 0.47 | 0.0584                                        | 0.0051                                         | 0.0621                                       | 0.0054                                        | 0.0080                                       | 0.0002                                        | 0.2509 |
| GK-21  | 7.27      | 490                      | 766                     | 0.64 | 0.0514                                        | 0.0029                                         | 0.0545                                       | 0.0029                                        | 0.0077                                       | 0.0001                                        | 0.2488 |
| GK-22  | 3.09      | 136                      | 311                     | 0.44 | 0.0664                                        | 0.0045                                         | 0.0731                                       | 0.0048                                        | 0.0082                                       | 0.0002                                        | 0.3744 |
| GK-23  | 6.17      | 456                      | 628                     | 0.73 | 0.0559                                        | 0.0042                                         | 0.0594                                       | 0.0041                                        | 0.0079                                       | 0.0001                                        | 0.2181 |
| GK-24  | 3.26      | 191                      | 333                     | 0.57 | 0.0758                                        | 0.0068                                         | 0.0805                                       | 0.0069                                        | 0.0080                                       | 0.0002                                        | 0.2473 |
| DK-01  | 5.64      | 454                      | 523                     | 0.87 | 0.0507                                        | 0.0023                                         | 0.0566                                       | 0.0025                                        | 0.0082                                       | 0.0001                                        | 0.2641 |
| DK-02  | 5.77      | 404                      | 555                     | 0.73 | 0.0468                                        | 0.0022                                         | 0.0522                                       | 0.0024                                        | 0.0082                                       | 0.0001                                        | 0.2444 |
| DK-03  | 8.88      | 709                      | 815                     | 0.87 | 0.0466                                        | 0.0020                                         | 0.0526                                       | 0.0022                                        | 0.0082                                       | 0.0001                                        | 0.2285 |
| DK-04  | 9.98      | 777                      | 895                     | 0.87 | 0.0488                                        | 0.0018                                         | 0.0569                                       | 0.0021                                        | 0.0085                                       | 0.0001                                        | 0.2699 |
| DK-05  | 26.86     | 1795                     | 2531                    | 0.71 | 0.0467                                        | 0.0011                                         | 0.0547                                       | 0.0013                                        | 0.0085                                       | 0.0001                                        | 0.3647 |
| DK-06  | 10.21     | 829                      | 914                     | 0.91 | 0.0465                                        | 0.0018                                         | 0.0547                                       | 0.0021                                        | 0.0085                                       | 0.0001                                        | 0.3267 |
| DK-07  | 7.75      | 595                      | 731                     | 0.81 | 0.0472                                        | 0.0019                                         | 0.0536                                       | 0.0022                                        | 0.0082                                       | 0.0001                                        | 0.2584 |
| DK-08  | 9.30      | 734                      | 829                     | 0.88 | 0.0491                                        | 0.0022                                         | 0.0573                                       | 0.0026                                        | 0.0084                                       | 0.0001                                        | 0.2350 |
| DK-09  | 6.92      | 460                      | 651                     | 0.71 | 0.0460                                        | 0.0022                                         | 0.0533                                       | 0.0025                                        | 0.0085                                       | 0.0001                                        | 0.2088 |
| DK-10  | 7.64      | 617                      | 678                     | 0.91 | 0.0471                                        | 0.0020                                         | 0.0549                                       | 0.0023                                        | 0.0085                                       | 0.0001                                        | 0.2890 |
| DK-12  | 26.3      | 2192                     | 2351                    | 0.93 | 0.0462                                        | 0.0011                                         | 0.0538                                       | 0.0013                                        | 0.0085                                       | 0.0001                                        | 0.4858 |
| DK-13  | 29.51     | 1213                     | 2994                    | 0.41 | 0.0473                                        | 0.0011                                         | 0.0548                                       | 0.0012                                        | 0.0084                                       | 0.0001                                        | 0.3764 |
| DK-14  | 8.48      | 654                      | 763                     | 0.86 | 0.0498                                        | 0.0026                                         | 0.0577                                       | 0.0029                                        | 0.0085                                       | 0.0001                                        | 0.1915 |
| DK-15  | 45.7      | 2615                     | 4259                    | 0.61 | 0.0494                                        | 0.0010                                         | 0.0582                                       | 0.0012                                        | 0.0085                                       | 0.0001                                        | 0.4238 |
| NS_01  | 20.3      | 471                      | 1504                    | 0.31 | 0.0968                                        | 0.0105                                         | 0.0746                                       | 0.0079                                        | 0.0056                                       | 0.0001                                        | 0.1450 |
| NS_02  | 2.48      | 211                      | 367                     | 0.57 | 0.0622                                        | 0.0060                                         | 0.0450                                       | 0.0039                                        | 0.0057                                       | 0.0002                                        | 0.3128 |
| NS_03  | 1.88      | 141                      | 245                     | 0.57 | 0.1239                                        | 0.0139                                         | 0.0904                                       | 0.0096                                        | 0.0057                                       | 0.0002                                        | 0.2785 |
| NS_04  | 2.51      | 178                      | 352                     | 0.50 | 0.0742                                        | 0.0093                                         | 0.0528                                       | 0.0060                                        | 0.0057                                       | 0.0002                                        | 0.2355 |
| NS_05  | 1.32      | 109                      | 191                     | 0.57 | 0.0786                                        | 0.0198                                         | 0.0471                                       | 0.0066                                        | 0.0056                                       | 0.0002                                        | 0.2342 |
| NS_06  | 5.81      | 468                      | 785                     | 0.60 | 0.0861                                        | 0.0064                                         | 0.0659                                       | 0.0048                                        | 0.0056                                       | 0.0001                                        | 0.2095 |
| NS_07  | 5.27      | 403                      | 718                     | 0.56 | 0.0843                                        | 0.0063                                         | 0.0679                                       | 0.0048                                        | 0.0058                                       | 0.0001                                        | 0.3227 |
| NS_08  | 2.40      | 187                      | 286                     | 0.65 | 0.1206                                        | 0.0146                                         | 0.0870                                       | 0.0093                                        | 0.0057                                       | 0.0002                                        | 0.2699 |
| NS_09  | 3.09      | 239                      | 384                     | 0.62 | 0.1182                                        | 0.0115                                         | 0.0940                                       | 0.0096                                        | 0.0057                                       | 0.0001                                        | 0.2477 |
| NS_10  | 1.78      | 151                      | 220                     | 0.68 | 0.1187                                        | 0.0137                                         | 0.0836                                       | 0.0078                                        | 0.0058                                       | 0.0002                                        | 0.3547 |
| NS_11  | 4.83      | 416                      | 715                     | 0.58 | 0.0473                                        | 0.0046                                         | 0.0365                                       | 0.0037                                        | 0.0057                                       | 0.0001                                        | 0.2385 |
| MH_01  | 2.18      | 218                      | 286                     | 0.76 | 0.0737                                        | 0.0064                                         | 0.0606                                       | 0.0050                                        | 0.0057                                       | 0.0001                                        | 0.3048 |
| MH_02  | 3.01      | 257                      | 368                     | 0.70 | 0.1294                                        | 0.0129                                         | 0.0899                                       | 0.0075                                        | 0.0057                                       | 0.0002                                        | 0.3851 |
| MH_03  | 12.10     | 2035                     | 1354                    | 1.50 | 0.0495                                        | 0.0037                                         | 0.0382                                       | 0.0026                                        | 0.0057                                       | 0.0001                                        | 0.2237 |
| MH_04  | 13.06     | 2116                     | 1467                    | 1.44 | 0.0477                                        | 0.0040                                         | 0.0370                                       | 0.0028                                        | 0.0058                                       | 0.0001                                        | 0.2825 |
| MH_05  | 2.59      | 267                      | 330                     | 0.81 | 0.0759                                        | 0.0085                                         | 0.0563                                       | 0.0056                                        | 0.0057                                       | 0.0001                                        | 0.2434 |
| MH_06  | 4.89      | 524                      | 648                     | 0.81 | 0.0498                                        | 0.0041                                         | 0.0380                                       | 0.0029                                        | 0.0057                                       | 0.0001                                        | 0.2367 |
| MH_07  | 1.59      | 130                      | 228                     | 0.57 | 0.0934                                        | 0.0109                                         | 0.0690                                       | 0.0073                                        | 0.0058                                       | 0.0002                                        | 0.2958 |
| MH_08  | 1.75      | 120                      | 244                     | 0.49 | 0.0894                                        | 0.0098                                         | 0.0647                                       | 0.0058                                        | 0.0057                                       | 0.0002                                        | 0.2975 |
| MH_11  | 3.92      | 470                      | 502                     | 0.94 | 0.0478                                        | 0.0051                                         | 0.0374                                       | 0.0037                                        | 0.0057                                       | 0.0001                                        | 0.2145 |
| MH_12  | 1.09      | 85.8                     | 166                     | 0.52 | 0.0792                                        | 0.0197                                         | 0.0487                                       | 0.0061                                        | 0.0057                                       | 0.0002                                        | 0.3218 |

TABLE II. Continued

| Sample | Pb<br>ppm | Th <sup>232</sup><br>ppm | U <sup>238</sup><br>ppm | Th/U | <sup>207</sup> Pb/ <sup>206</sup> Pb<br>Ratio | <sup>207</sup> Pb/ <sup>206</sup> Pb<br>1sigma | <sup>207</sup> Pb/ <sup>235</sup> U<br>Ratio | <sup>207</sup> Pb/ <sup>235</sup> U<br>1sigma | <sup>206</sup> Pb/ <sup>238</sup> U<br>Ratio | <sup>206</sup> Pb/ <sup>238</sup> U<br>1sigma | rho    |
|--------|-----------|--------------------------|-------------------------|------|-----------------------------------------------|------------------------------------------------|----------------------------------------------|-----------------------------------------------|----------------------------------------------|-----------------------------------------------|--------|
| ZF_01  | 0.47      | 40.7                     | 83.1                    | 0.49 | 1.1361                                        | 0.4612                                         | 0.1638                                       | 0.0172                                        | 0.0038                                       | 0.0002                                        | 0.5844 |
| ZF_02  | 1.53      | 231                      | 263                     | 0.88 | 0.1104                                        | 0.0156                                         | 0.0520                                       | 0.0063                                        | 0.0041                                       | 0.0001                                        | 0.2925 |
| ZF_04  | 1.29      | 210                      | 257                     | 0.82 | 0.0970                                        | 0.0142                                         | 0.0454                                       | 0.0062                                        | 0.0039                                       | 0.0001                                        | 0.2391 |
| ZF_05  | 0.66      | 63.5                     | 112                     | 0.57 | 0.4159                                        | 0.1342                                         | 0.1112                                       | 0.0146                                        | 0.0041                                       | 0.0003                                        | 0.4923 |
| ZF_06  | 0.37      | 42.8                     | 88.8                    | 0.48 | 0.2869                                        | 0.0664                                         | 0.0918                                       | 0.0121                                        | 0.0036                                       | 0.0002                                        | 0.4152 |
| ZF_08  | 1.32      | 255                      | 251                     | 1.02 | 0.0536                                        | 0.0106                                         | 0.0266                                       | 0.0050                                        | 0.0038                                       | 0.0002                                        | 0.2484 |
| ZF_09  | 0.88      | 80.6                     | 162                     | 0.50 | 0.6727                                        | 0.4692                                         | 0.0776                                       | 0.0080                                        | 0.0038                                       | 0.0002                                        | 0.3921 |
| ZF_10  | 0.44      | 45.9                     | 105                     | 0.44 | 0.2381                                        | 0.0699                                         | 0.0740                                       | 0.0136                                        | 0.0037                                       | 0.0002                                        | 0.3286 |
| ZF_11  | 0.67      | 69.0                     | 131                     | 0.53 | 0.3338                                        | 0.1083                                         | 0.0924                                       | 0.0099                                        | 0.0038                                       | 0.0002                                        | 0.4249 |
| ZF_12  | 1.40      | 166                      | 306                     | 0.54 | 0.1179                                        | 0.0114                                         | 0.0536                                       | 0.0049                                        | 0.0037                                       | 0.0001                                        | 0.3493 |
| ZF_13  | 1.03      | 154                      | 215                     | 0.72 | 0.1363                                        | 0.0193                                         | 0.0605                                       | 0.0074                                        | 0.0038                                       | 0.0001                                        | 0.2741 |
| ZF_14  | 0.55      | 56.9                     | 116                     | 0.49 | 0.1133                                        | 0.0189                                         | 0.0484                                       | 0.0068                                        | 0.0039                                       | 0.0002                                        | 0.3050 |
| ZF_15  | 2.00      | 410                      | 349                     | 1.18 | 0.1054                                        | 0.0106                                         | 0.0482                                       | 0.0044                                        | 0.0038                                       | 0.0001                                        | 0.3083 |
| FS_01  | 0.88      | 208                      | 203                     | 1.02 | 0.0331                                        | 0.0141                                         | 0.0238                                       | 0.0073                                        | 0.0032                                       | 0.0002                                        | 0.1882 |
| FS_03  | 0.50      | 99.0                     | 113                     | 0.88 | 0.0000                                        | 0.0000                                         | 0.0578                                       | 0.0106                                        | 0.0031                                       | 0.0002                                        | 0.3577 |
| FS_05  | 0.48      | 60.3                     | 133                     | 0.45 | 0.3650                                        | 0.2457                                         | 0.0485                                       | 0.0059                                        | 0.0032                                       | 0.0002                                        | 0.4048 |
| FS_06  | 0.199     | 18.4                     | 56.1                    | 0.33 | 0.6247                                        | 0.1521                                         | 0.0766                                       | 0.0117                                        | 0.0032                                       | 0.0003                                        | 0.5500 |
| FS_07  | 0.90      | 178                      | 230                     | 0.77 | 0.1119                                        | 0.0236                                         | 0.0330                                       | 0.0042                                        | 0.0032                                       | 0.0001                                        | 0.3147 |
| FS_10  | 0.93      | 127                      | 252                     | 0.50 | 0.1084                                        | 0.0131                                         | 0.0431                                       | 0.0043                                        | 0.0031                                       | 0.0001                                        | 0.4398 |
| FS_12  | 0.52      | 70.4                     | 123                     | 0.57 | 0.2894                                        | 0.0753                                         | 0.0681                                       | 0.0079                                        | 0.0032                                       | 0.0002                                        | 0.4522 |
| FS_15  | 0.35      | 58.9                     | 96.4                    | 0.61 | 0.8626                                        | 0.2674                                         | 0.0765                                       | 0.0126                                        | 0.0032                                       | 0.0002                                        | 0.4627 |

TABLE II. Continued

| Sample | $^{208}\text{Pb}/^{232}\text{Th}$<br>Ratio | $^{208}\text{Pb}/^{232}\text{Th}$<br>1sigma | $^{238}\text{U}/^{232}\text{Th}$<br>Ratio | $^{207}\text{Pb}/^{206}\text{Pb}$<br>Age (Ma) | $^{207}\text{Pb}/^{206}\text{Pb}$<br>1sigma | $^{207}\text{Pb}/^{235}\text{U}$<br>Age (Ma) | $^{207}\text{Pb}/^{235}\text{U}$<br>1sigma | $^{206}\text{Pb}/^{238}\text{U}$<br>Age (Ma) | $^{206}\text{Pb}/^{238}\text{U}$<br>1sigma | $^{208}\text{Pb}/^{232}\text{Th}$<br>Age (Ma) | $^{208}\text{Pb}/^{232}\text{Th}$<br>1sigma |
|--------|--------------------------------------------|---------------------------------------------|-------------------------------------------|-----------------------------------------------|---------------------------------------------|----------------------------------------------|--------------------------------------------|----------------------------------------------|--------------------------------------------|-----------------------------------------------|---------------------------------------------|
| GK-01  | 0.0034                                     | 0.0001                                      | 1.5972                                    | 1106                                          | 138                                         | 83.6                                         | 6.1                                        | 51.5                                         | 1.1                                        | 67.7                                          | 2.8                                         |
| GK-02  | 0.0029                                     | 0.0002                                      | 2.4262                                    | 981                                           | 192                                         | 70.1                                         | 5.4                                        | 51.2                                         | 1.4                                        | 57.9                                          | 4.8                                         |
| GK-03  | 0.0027                                     | 0.0001                                      | 1.7365                                    | 154                                           | 148                                         | 52.6                                         | 3.3                                        | 51.6                                         | 0.9                                        | 55.2                                          | 2.7                                         |
| GK-04  | 0.0024                                     | 0.0001                                      | 1.5277                                    | 346                                           | 194                                         | 57.5                                         | 5.0                                        | 51.1                                         | 1.1                                        | 49.1                                          | 2.4                                         |
| GK-05  | 0.0032                                     | 0.0002                                      | 2.1829                                    | 1280                                          | 171                                         | 82.5                                         | 6.0                                        | 51.6                                         | 1.4                                        | 63.8                                          | 4.2                                         |
| GK-06  | 0.0024                                     | 0.0002                                      | 2.0671                                    | 569                                           | 163                                         | 62.5                                         | 4.6                                        | 51.2                                         | 1.3                                        | 49.0                                          | 3.3                                         |
| GK-07  | 0.0029                                     | 0.0002                                      | 2.5888                                    | 680                                           | 234                                         | 64.0                                         | 6.2                                        | 51.3                                         | 1.3                                        | 57.9                                          | 3.8                                         |
| GK-08  | 0.0025                                     | 0.0001                                      | 1.7332                                    | 502                                           | 204                                         | 57.8                                         | 4.8                                        | 50.3                                         | 1.2                                        | 51.4                                          | 2.5                                         |
| GK-09  | 0.0028                                     | 0.0001                                      | 1.5768                                    | 391                                           | 206                                         | 57.6                                         | 4.5                                        | 52.5                                         | 1.0                                        | 57.5                                          | 2.4                                         |
| GK-10  | 0.0026                                     | 0.0001                                      | 1.0709                                    | 239                                           | 153                                         | 55.0                                         | 3.2                                        | 50.9                                         | 0.7                                        | 52.1                                          | 1.7                                         |
| GK-11  | 0.0027                                     | 0.0001                                      | 1.3203                                    | 372                                           | 126                                         | 58.6                                         | 3.2                                        | 51.1                                         | 0.7                                        | 54.5                                          | 1.7                                         |
| GK-12  | 0.0031                                     | 0.0001                                      | 1.0839                                    | 792                                           | 157                                         | 72.8                                         | 5.2                                        | 52.9                                         | 0.8                                        | 63.1                                          | 2.1                                         |
| GK-13  | 0.0032                                     | 0.0005                                      | 2.1594                                    | 524                                           | 191                                         | 59.3                                         | 4.7                                        | 50.5                                         | 0.9                                        | 64.7                                          | 10.3                                        |
| GK-14  | 0.0029                                     | 0.0002                                      | 2.4132                                    | 694                                           | 168                                         | 65.7                                         | 5.0                                        | 50.8                                         | 1.1                                        | 58.1                                          | 3.4                                         |
| GK-15  | 0.0027                                     | 0.0001                                      | 1.5334                                    | 569                                           | 193                                         | 60.8                                         | 5.2                                        | 49.6                                         | 1.0                                        | 53.5                                          | 2.6                                         |
| GK-16  | 0.0028                                     | 0.0001                                      | 1.7750                                    | 409                                           | 167                                         | 56.5                                         | 3.6                                        | 49.8                                         | 1.0                                        | 56.5                                          | 3.0                                         |
| GK-17  | 0.0034                                     | 0.0002                                      | 2.2404                                    | 672                                           | 166                                         | 68.7                                         | 5.1                                        | 53.4                                         | 1.2                                        | 68.3                                          | 4.0                                         |
| GK-18  | 0.0032                                     | 0.0002                                      | 2.2516                                    | 754                                           | 181                                         | 69.0                                         | 5.8                                        | 51.3                                         | 1.2                                        | 64.4                                          | 4.4                                         |
| GK-19  | 0.0019                                     | 0.0001                                      | 2.2674                                    | 546                                           | 194                                         | 61.2                                         | 5.1                                        | 51.5                                         | 1.1                                        | 39.2                                          | 2.8                                         |
| GK-21  | 0.0027                                     | 0.0001                                      | 1.6779                                    | 261                                           | 128                                         | 53.8                                         | 2.8                                        | 49.7                                         | 0.7                                        | 54.5                                          | 1.8                                         |
| GK-22  | 0.0035                                     | 0.0002                                      | 2.4326                                    | 820                                           | 141                                         | 71.6                                         | 4.5                                        | 52.9                                         | 1.3                                        | 70.6                                          | 4.9                                         |
| GK-23  | 0.0026                                     | 0.0001                                      | 1.4657                                    | 456                                           | 167                                         | 58.6                                         | 4.0                                        | 50.6                                         | 0.8                                        | 52.9                                          | 1.8                                         |
| GK-24  | 0.0029                                     | 0.0002                                      | 1.8637                                    | 1100                                          | 180                                         | 78.6                                         | 6.5                                        | 51.2                                         | 1.1                                        | 58.9                                          | 4.0                                         |
| DK-01  | 0.0026                                     | 0.0001                                      | 1.1562                                    | 233                                           | 106                                         | 55.9                                         | 2.4                                        | 52.4                                         | 0.6                                        | 53.0                                          | 1.3                                         |
| DK-02  | 0.0027                                     | 0.0001                                      | 1.3632                                    | 39                                            | 111                                         | 51.7                                         | 2.3                                        | 52.3                                         | 0.6                                        | 54.2                                          | 1.5                                         |
| DK-03  | 0.0028                                     | 0.0001                                      | 1.1377                                    | 31.6                                          | 100.0                                       | 52.1                                         | 2.2                                        | 52.7                                         | 0.5                                        | 57.2                                          | 1.3                                         |
| DK-04  | 0.0028                                     | 0.0001                                      | 1.1421                                    | 139                                           | 89                                          | 56.2                                         | 2.0                                        | 54.5                                         | 0.5                                        | 57.5                                          | 1.1                                         |
| DK-05  | 0.0030                                     | 0.0001                                      | 1.4411                                    | 31.6                                          | 55.6                                        | 54.1                                         | 1.3                                        | 54.3                                         | 0.5                                        | 59.8                                          | 1.0                                         |
| DK-06  | 0.0030                                     | 0.0001                                      | 1.0870                                    | 33.43                                         | 88.9                                        | 54.1                                         | 2.1                                        | 54.8                                         | 0.7                                        | 61.0                                          | 1.4                                         |
| DK-07  | 0.0027                                     | 0.0001                                      | 1.2384                                    | 58                                            | 96                                          | 53.0                                         | 2.1                                        | 52.9                                         | 0.5                                        | 54.3                                          | 1.3                                         |
| DK-08  | 0.0030                                     | 0.0001                                      | 1.1131                                    | 150                                           | 104                                         | 56.6                                         | 2.5                                        | 54.2                                         | 0.6                                        | 60.7                                          | 1.3                                         |
| DK-09  | 0.0027                                     | 0.0001                                      | 1.4006                                    | *                                             |                                             | 52.7                                         | 2.4                                        | 54.3                                         | 0.5                                        | 55.4                                          | 1.3                                         |
| DK-10  | 0.0028                                     | 0.0001                                      | 1.0737                                    | 53.8                                          | 100.0                                       | 54.3                                         | 2.2                                        | 54.7                                         | 0.7                                        | 56.8                                          | 1.2                                         |
| DK-12  | 0.0028                                     | 0.0001                                      | 1.0926                                    | 5.66                                          | 55.6                                        | 53.2                                         | 1.2                                        | 54.3                                         | 0.6                                        | 56.6                                          | 1.1                                         |
| DK-13  | 0.0026                                     | 0.0000                                      | 2.4407                                    | 64.9                                          | 51.8                                        | 54.2                                         | 1.2                                        | 53.9                                         | 0.4                                        | 53.4                                          | 1.0                                         |
| DK-14  | 0.0025                                     | 0.0001                                      | 1.1361                                    | 187                                           | 122                                         | 57.0                                         | 2.8                                        | 54.3                                         | 0.5                                        | 50.6                                          | 1.2                                         |
| DK-15  | 0.0028                                     | 0.0000                                      | 1.5815                                    | 169                                           | 46                                          | 57.5                                         | 1.1                                        | 54.8                                         | 0.5                                        | 56.4                                          | 0.9                                         |
| NS_01  | 0.0040                                     | 0.0003                                      | 3.2681                                    | 1565                                          | 203.7                                       | 73                                           | 7.5                                        | 36.1                                         | 0.6                                        | 81                                            | 6.7                                         |
| NS_02  | 0.0019                                     | 0.0001                                      | 1.7937                                    | 681                                           | 206                                         | 44.7                                         | 3.8                                        | 36.3                                         | 1.0                                        | 38.3                                          | 2.6                                         |
| NS_03  | 0.0030                                     | 0.0002                                      | 1.7951                                    | 2013                                          | 206                                         | 88                                           | 8.9                                        | 36.9                                         | 1.1                                        | 61.0                                          | 4.8                                         |
| NS_04  | 0.0025                                     | 0.0002                                      | 2.1014                                    | 1056                                          | 256                                         | 52.2                                         | 5.8                                        | 36.5                                         | 1.0                                        | 50.2                                          | 3.0                                         |
| NS_05  | 0.0026                                     | 0.0002                                      | 1.8141                                    | 1163                                          | 514                                         | 46.7                                         | 6.4                                        | 36.3                                         | 1.2                                        | 52.9                                          | 3.8                                         |
| NS_06  | 0.0023                                     | 0.0001                                      | 1.7624                                    | 1340                                          | 143                                         | 64.8                                         | 4.6                                        | 36.3                                         | 0.6                                        | 47.0                                          | 3.0                                         |
| NS_07  | 0.0028                                     | 0.0002                                      | 1.7594                                    | 1302                                          | 144.4                                       | 66.7                                         | 4.6                                        | 37.3                                         | 0.9                                        | 56.4                                          | 3.5                                         |
| NS_08  | 0.0030                                     | 0.0002                                      | 1.7938                                    | 1966                                          | 218.1                                       | 84.7                                         | 8.7                                        | 36.8                                         | 1.1                                        | 61.2                                          | 4.8                                         |
| NS_09  | 0.0033                                     | 0.0003                                      | 1.6766                                    | 1929                                          | 175                                         | 91                                           | 8.9                                        | 36.3                                         | 0.9                                        | 68                                            | 6.2                                         |
| NS_10  | 0.0027                                     | 0.0002                                      | 1.5674                                    | 1939                                          | 207                                         | 81.6                                         | 7.3                                        | 37.4                                         | 1.2                                        | 54.7                                          | 4.2                                         |
| NS_11  | 0.0017                                     | 0.0001                                      | 1.8552                                    | 61                                            | 218                                         | 36.4                                         | 3.6                                        | 36.5                                         | 0.9                                        | 34.1                                          | 2.3                                         |
| MH_01  | 0.0020                                     | 0.0001                                      | 1.4148                                    | 1035                                          | 175                                         | 59.8                                         | 4.8                                        | 36.8                                         | 0.9                                        | 41.4                                          | 2.3                                         |
| MH_02  | 0.0027                                     | 0.0002                                      | 1.4880                                    | 2090                                          | 177.0                                       | 87                                           | 7.0                                        | 36.6                                         | 1.2                                        | 53.6                                          | 3.8                                         |
| MH_03  | 0.0019                                     | 0.0001                                      | 0.6940                                    | 172                                           | 172                                         | 38.1                                         | 2.5                                        | 36.9                                         | 0.6                                        | 38.7                                          | 1.1                                         |
| MH_04  | 0.0021                                     | 0.0001                                      | 0.7391                                    | 83                                            | 250.0                                       | 36.9                                         | 2.7                                        | 37.1                                         | 0.8                                        | 42.2                                          | 1.3                                         |
| MH_05  | 0.0022                                     | 0.0001                                      | 1.4289                                    | 1092                                          | 226                                         | 55.6                                         | 5.4                                        | 36.7                                         | 0.9                                        | 45.4                                          | 2.7                                         |
| MH_06  | 0.0019                                     | 0.0001                                      | 1.2888                                    | 183                                           | 181                                         | 37.9                                         | 2.9                                        | 36.8                                         | 0.7                                        | 39.1                                          | 1.5                                         |
| MH_07  | 0.0021                                     | 0.0002                                      | 1.8126                                    | 1495                                          | 222                                         | 67.8                                         | 6.9                                        | 37.1                                         | 1.2                                        | 41.6                                          | 3.6                                         |
| MH_08  | 0.0026                                     | 0.0001                                      | 2.1190                                    | 1413                                          | 212                                         | 63.7                                         | 5.5                                        | 36.5                                         | 1.0                                        | 53.1                                          | 2.9                                         |
| MH_11  | 0.0023                                     | 0.0001                                      | 1.0979                                    | 87                                            | 237                                         | 37.3                                         | 3.7                                        | 36.8                                         | 0.8                                        | 46.8                                          | 2.2                                         |
| MH_12  | 0.0024                                     | 0.0002                                      | 1.9919                                    | 1177                                          | 511                                         | 48.3                                         | 5.9                                        | 36.6                                         | 1.5                                        | 48.0                                          | 4.8                                         |
| ZF_01  | 0.0040                                     | 0.0004                                      | 2.1053                                    | *                                             | *                                           | 154                                          | 15.0                                       | 24.7                                         | 1.5                                        | 80.7                                          | 7.1                                         |
| ZF_02  | 0.0020                                     | 0.0001                                      | 1.1678                                    | 1806                                          | 259.6                                       | 51.5                                         | 6.1                                        | 26.4                                         | 0.9                                        | 39.9                                          | 2.7                                         |
| ZF_04  | 0.0016                                     | 0.0001                                      | 1.2766                                    | 1569                                          | 277                                         | 45.1                                         | 6.0                                        | 24.8                                         | 0.8                                        | 31.7                                          | 2.3                                         |
| ZF_05  | 0.0041                                     | 0.0004                                      | 1.8990                                    | 3968                                          | 505                                         | 107                                          | 13.4                                       | 26.1                                         | 1.7                                        | 83.5                                          | 8.0                                         |
| ZF_06  | 0.0035                                     | 0.0003                                      | 2.1598                                    | 3401                                          | 369                                         | 89.1                                         | 11.3                                       | 23.0                                         | 1.3                                        | 69.9                                          | 6.6                                         |
| ZF_08  | 0.0016                                     | 0.0001                                      | 1.0648                                    | 354                                           | 394                                         | 26.7                                         | 5.0                                        | 24.7                                         | 1.2                                        | 31.6                                          | 2.7                                         |
| ZF_09  | 0.0031                                     | 0.0003                                      | 2.1477                                    | 4673                                          | 1819                                        | 75.9                                         | 7.5                                        | 24.7                                         | 1.0                                        | 61.7                                          | 5.9                                         |
| ZF_10  | 0.0033                                     | 0.0003                                      | 2.3969                                    | 3107                                          | 485                                         | 72.5                                         | 12.8                                       | 23.6                                         | 1.4                                        | 66.0                                          | 6.3                                         |
| ZF_11  | 0.0026                                     | 0.0002                                      | 1.9617                                    | 3635                                          | 519                                         | 89.7                                         | 9.2                                        | 24.2                                         | 1.1                                        | 52.5                                          | 4.6                                         |



TABLE II. Continued

| Sample | $^{208}\text{Pb}/^{232}\text{Th}$<br>Ratio | $^{208}\text{Pb}/^{232}\text{Th}$<br>1sigma | $^{238}\text{U}/^{232}\text{Th}$<br>Ratio | $^{207}\text{Pb}/^{206}\text{Pb}$<br>Age (Ma) | $^{207}\text{Pb}/^{206}\text{Pb}$<br>1sigma | $^{207}\text{Pb}/^{235}\text{U}$<br>Age (Ma) | $^{207}\text{Pb}/^{235}\text{U}$<br>1sigma | $^{206}\text{Pb}/^{238}\text{U}$<br>Age (Ma) | $^{206}\text{Pb}/^{238}\text{U}$<br>1sigma | $^{208}\text{Pb}/^{232}\text{Th}$<br>Age (Ma) | $^{208}\text{Pb}/^{232}\text{Th}$<br>1sigma |
|--------|--------------------------------------------|---------------------------------------------|-------------------------------------------|-----------------------------------------------|---------------------------------------------|----------------------------------------------|--------------------------------------------|----------------------------------------------|--------------------------------------------|-----------------------------------------------|---------------------------------------------|
| ZF_12  | 0.0017                                     | 0.0001                                      | 2.3132                                    | 1924                                          | 173                                         | 53.0                                         | 4.7                                        | 23.8                                         | 0.8                                        | 34.2                                          | 2.9                                         |
| ZF_13  | 0.0012                                     | 0.0001                                      | 1.4815                                    | 2181                                          | 249                                         | 59.6                                         | 7.1                                        | 24.5                                         | 0.8                                        | 24.5                                          | 2.4                                         |
| ZF_14  | 0.0022                                     | 0.0002                                      | 2.1421                                    | 1854                                          | 306                                         | 48.0                                         | 6.5                                        | 24.9                                         | 1.1                                        | 45.3                                          | 4.4                                         |
| ZF_15  | 0.0014                                     | 0.0001                                      | 0.8827                                    | 1722                                          | 187                                         | 47.8                                         | 4.3                                        | 24.4                                         | 0.7                                        | 29.2                                          | 1.7                                         |
| FS_01  | 0.0017                                     | 0.0002                                      | 1.2271                                    | *                                             | *                                           | 23.9                                         | 7.2                                        | 20.8                                         | 1.2                                        | 34.1                                          | 3.7                                         |
| FS_03  | 0.0021                                     | 0.0002                                      | 1.1936                                    | *                                             | *                                           | 57.1                                         | 10.2                                       | 20.1                                         | 1.3                                        | 43.3                                          | 3.9                                         |
| FS_05  | 0.0019                                     | 0.0002                                      | 2.3017                                    | 3771                                          | 1294                                        | 48.0                                         | 5.7                                        | 20.3                                         | 1.0                                        | 38.5                                          | 4.2                                         |
| FS_06  | 0.0049                                     | 0.0006                                      | 3.2029                                    | 4567                                          | 409                                         | 75.0                                         | 11.0                                       | 20.6                                         | 1.7                                        | 98.1                                          | 12.4                                        |
| FS_07  | 0.0011                                     | 0.0001                                      | 1.3537                                    | 1831                                          | 391                                         | 33.0                                         | 4.2                                        | 20.5                                         | 0.8                                        | 22.7                                          | 2.0                                         |
| FS_10  | 0.0012                                     | 0.0002                                      | 2.0605                                    | 1773                                          | 222                                         | 42.9                                         | 4.2                                        | 20.3                                         | 0.9                                        | 24.2                                          | 3.6                                         |
| FS_12  | 0.0017                                     | 0.0002                                      | 1.8118                                    | 3415                                          | 417                                         | 66.9                                         | 7.6                                        | 20.8                                         | 1.1                                        | 34.0                                          | 4.0                                         |
| FS_15  | 0.0022                                     | 0.0003                                      | 1.6987                                    | *                                             | *                                           | 74.8                                         | 11.8                                       | 20.6                                         | 1.6                                        | 44.4                                          | 5.6                                         |

**TABLE III.** U-Pb data for intrusive rocks in the Ardestan area

| Locality   | Number of sites | Type rocks   | Age           | MSWD  | Figure |
|------------|-----------------|--------------|---------------|-------|--------|
| Kuh-e Dom  |                 | diorite      | 53.90 ±0.40Ma | 1.18  | 9A     |
| Kuh-e Dom  | 37              | granodiorite | 51.10±0.40Ma  | 1.04  | 9B     |
| Mehrabad   | 10              | granodiorite | 36.8±0.5Ma    | 0.047 | 9C     |
| Nasrand    | 11              | granodiorite | 36.5±0.5Ma    | 0.23  | 9D     |
| Zafarghand | 13              | granodiorite | 24.6±0.5Ma    | 0.66  | 9E     |
| Feshark    | 8               | granodiorite | 20.5±0.8Ma    | 0.045 | 9F     |

MSWD: Mean Squared Weighted Deviates

**TABLE IV.** Some reported radiometric ages of UDMA plutonic rocks

| Locality                       | Type rocks                        | Age (Ma)    | Epoch                | Reference                      |
|--------------------------------|-----------------------------------|-------------|----------------------|--------------------------------|
| Shir-Kuh                       | granodiorite-diorite              | 166.0-166.8 | Middle Jurassic      | Chiu <i>et al.</i> , 2013      |
| Bazman area                    | gabbro to granite                 | 81–72       | Late Cretaceous      | Chiu <i>et al.</i> , 2014      |
| Bam-Jiroft                     | gabbro                            | 76.6        | Late Cretaceous      | Chiu <i>et al.</i> , 2015      |
| Mozvash at the Kashan          | microdiorite                      | 50.1        | Early Eocene         | Honarmand <i>et al.</i> , 2013 |
| Khalkhab- Siljerd at the Saveh | monzogabbro/diorite, granodiorite | 36.6–40.3   | Upper Eocene         | Rezaei <i>et al.</i> , 2011    |
| between Kashan and Natanz      | microdiorite                      | 33          | Oligocene            | Chiu <i>et al.</i> , 2013      |
| Rigan near Bam                 | granitic rocks                    | 29          | Oligocene            | McInnes <i>et al.</i> , 2003   |
| Bam-Jiroft areas               | diorite                           | 29.9        | upper Oligocene      | Chiu <i>et al.</i> , 2013      |
| South of Kerman                | diorite                           | 30–24       | Upper Oligocene      | Chiu <i>et al.</i> , 2013      |
| Natanz area                    | granitic rocks                    | 21.2–19.6   | Miocene              | Chiu <i>et al.</i> , 2013      |
| Ghalhar, Niyasar, and Poudalg  | diorite                           | 18.21       | Lower-Middle Miocene | Honarmand <i>et al.</i> , 2013 |
| between Kashan and Natanz      | diorite                           | 16          | Middle Miocene       | Chiu <i>et al.</i> , 2013      |
| southwest of Qom               | granodiorite                      | 17.4        | Middle Miocene       | Chiu <i>et al.</i> , 2013      |
| Anar-Sirjan-Kerman             | granodiorite, diorite             | 9.4–5.4     | Upper Miocene        | Chiu <i>et al.</i> , 2013      |