Provenance of Upper Devonian Ilanqareh Formation (NW Iran), assessed using petrography and major element geochemistry

Origen de la Formación Ilanqareh (NW Irán) del Devónico Superior, evaluado por medio de petrografía y geoquímica de elementos mayores

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How to cite this article:
Anjerdi, J., Jafarzadeh, M., Najafzadeh, A., Mahari, R., 2022, Provenance of Upper Devonian Ilanqareh Formation (NW Iran), assessed using petrography and major element geochemistry: Boletín de la Sociedad Geológica Mexicana, 74 (3), A160722. http://dx.doi.org/10.18268/BSGM2022v74n3a160722

Manuscript received: April 15, 2022.
Corrected manuscript received: June 25, 2022.
Manuscript accepted: July 15, 2022.

Peer Reviewing under the responsibility of Universidad Nacional Autónoma de México.

ABSTRACT

In this study, a combination of petrographic and major element geochemical methods was employed on sandstones and shales of Upper Devonian Ilanqareh Formation, northwest of Iran, aimed at investigating the tectonic setting and the weathering degree of rocks in the source area. The index of compositional variability (ICV below 1) indicated that the studied quartzarenite and subarkose sandstones were not in the first cycle. Petrographic studies showed the existence of a craton interior provenance for these sandstones and geochemical studies identified recycling of older formations as an important source of these deposits. The chemical index of alteration (CIA values of 78.18 to 90.42 for sandstones and 91.55 to 91.93 for shale samples) indicated that the samples were affected by the high degree of weathering due to the humid climate in the source areas. Geochemical discrimination diagrams revealed that the samples were deposited in a passive margin. According to the paleogeography, this passive margin was the margin of a rift basin in the northwest of Gondwana, and the Ilanqareh deposits were derived from the Arabian-Nubian shield and the recycling of the Lower Palaeozoic sandstones in the region.

Keywords: Devonian, Northern Gondwana margin, Ilanqareh Formation, provenance, Tectonic setting, NW Iran.

RESUMEN

En este estudio, se empleó una combinación de métodos petrográficos y geoquímicos de elementos mayores en areniscas y lutitas de la Formación Ilanqareh del Devónico Superior, al noroeste de Irán, con el objetivo de investigar el entorno tectónico y el grado de meteorización de las rocas en esta área. El índice de variabilidad composicional (ICV por debajo de 1) indicó que las areniscas cuarzoareníticas y subarcosas estudiadas no se encontraban en el primer ciclo. Mientras, los estudios petrográficos mostraron la existencia de una procedencia interior del Cratón para estas areniscas, y los estudios geoquímicos identificaron el reciclaje de formaciones más antiguas como una fuente importante de estos depósitos. El índice químico de alteración (valores CIA de 78,18 a 90,42 para areniscas y de 91,55 a 91,93 para muestras de lutitas) indicó que las muestras se vieron afectadas por el alto grado de meteorización debido al clima húmedo en las áreas de origen. Los diagramas de discriminación geoquímica revelaron que las muestras se depositaron en un margen pasivo. Según la paleogeografía, este margen pasivo era típico de una cuenca de rift en el noroeste de Gondwana, y los depósitos de Ilanqareh se derivaron del escudo arábigo-nubio (ANS) y del reciclaje de las areniscas del Paleozoico Inferior en la región.

Palabras clave: Devónico, borde norte de Gondwana, Formación Ilanqareh, procedencia, entorno tectónico, NW Irán.

http://dx.doi.org/10.18268/BSGM2022v74n3a160722

1. Introduction

The whole-rock geochemical studies of siliciclastic sedimentary rocks can generally be used as additional data to petrography, and the combination of the two techniques is a powerful tool in determining rock composition, paleo-weathering, and tectonic setting of source terrains (Bhatia and Crook, 1986; McLennan *et al.*, 1993; Garzanti *et al.*, 1996; Ratcliffe *et al.*, 2007; Jafarzadeh *et al.*, 2014; Puy-Alquiza *et al.*, 2014; Verma and Armstrong-Altrin, 2016; Armstrong-Altrin *et al.*, 2017; Azizi *et al.*, 2018; Jafarzadeh *et al.*, 2022). During the Middle to Late Palaeozoic, parts of Iran, including Alborz mountain of Northern Iran, Central Iran, Sanandaj-Sirjan, and Northwestern Iran, along with several other plates, including the Afghan and Turkish plates, were connected to the African and Arabian plates and were regarded as a fragment of the southern margin of the Paleo-Tethys or in other words, part of the northwestern margin of Gondwana (Berberian and King, 1981; Sengor, 1990; Husseini, 1991, Ruban *et al.*, 2007; Horton *et al.*, 2008). The uplift and erosion caused by the late Devonian to Carboniferous Hercynian Orogeny prevented the simultaneous sediments from being distributed across the Arabian Peninsula. A regional comparison between the Upper Devonian to Lower Carboniferous sediments of Iran and other parts of the Middle East, such as Iraq, Turkey, Syria, and Saudi Arabia, showed that during this time, there was a vast continental margin that included North Africa and Saudi Arabia (Husseini, 1991).

Hitherto, many studies have been performed in various fields, including biostratigraphy, paleontology (Abbasi *et al.*, 2016), sequence stratigraphy, and sedimentology (Najafzadeh, 2008; Nekounam, 2016) on the Upper Devonian Ilanqareh Formation. In the meantime, few studies have been done on the provenance of its siliciclastic parts. Among these studies, very few attempts have been made to investigate the provenance with the aid of petrographic and whole rock geochemical analysis of siliciclastic rocks. Najafzadeh *et al.*, (2010) conducted the first study on the provenance of Ilanqareh sediments in Ilanlu and Ilanqareh outcrops using petrography and trace element geochemistry data. Anjerdi *et al.*, (2020) also examined the provenance of these sediments in the Pireshaq section

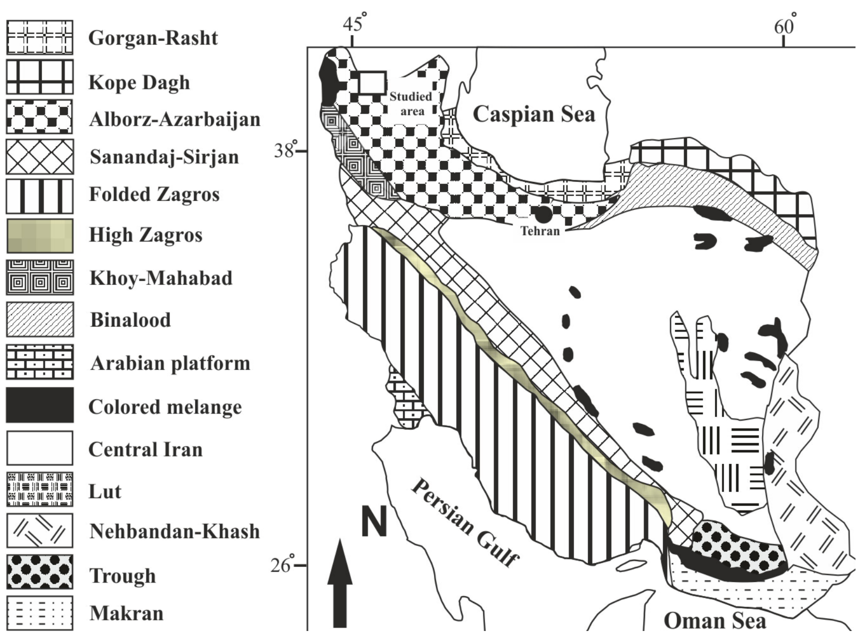

Figure 1 Major structural zones of Iran (after Nabavi, 1976) and the location of the studied area in the western Alborz-Azarbaijan zone.

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(south of Jolfa), which did not show a complete section of sediments of the Ilanqareh Formation, and its lower contact was faulted. Bónová *et al.*, (2021a) also studied detrital tourmaline and rutile grains separated from Ilanqareh sandstones and considered Arabian-Nubian Shield as a source for natural tourmaline grains and East African Belt for the unique V-rich tourmaline grains. Given the fact that the use of major element geochemistry is of special importance in provenance studies is among the particularly useful indicator for determining the provenance (Taylor and McLennan, 1985; Bhatia and Crook, 1986; Roser and Korsch, 1986; McLennan and Taylor, 1991; Bauluz *et al.*, 2000; Verma and Armstrong-Altrin, 2013; Taheri *et al.*, 2018; Moghaddam *et al.*, 2020), this study has sought to check the possible source rocks, tectonic setting of the source area, and the intensity of weathering at the time of sedimentation of Ilanqareh Formation using a combination of petrographic and major element geochemical methods at Ilanlu section in Azarbaijan Province, NW Iran.

2. Geological setting

Iranian Plateau is a tectonically active region within the Alpine–Himalayan orogenic belt and stands at a compressional zone between two rigid convergent blocks (Arabia and Eurasia) (Berberian and King, 1981). In the classification of the structural units of Iran (Nabavi, 1976), this area is situated in the western Alborz-Azarbaijan zone (Figure 1), which is part of the Alpine-Himalayan fold belt. During the Devonian, Alborz-Azarbaijan Range was part of the northern edge of the Gondwana, which was moving toward the north due to convergence with Laurasia in the north (Berberian and King, 1981).

The Devonian siliciclastic-carbonate deposits of the Ilanqareh Formation in the Azarbaijan district of Iran are the western continuation of similar deposits (Jeirud Formation) in the central Alborz (Wendt *et al.*, 2005). Comparison of the Ilanqareh Formation with the Upper Palaeozoic formations in other areas of the Middle East shows that during the deposition of these sediments,

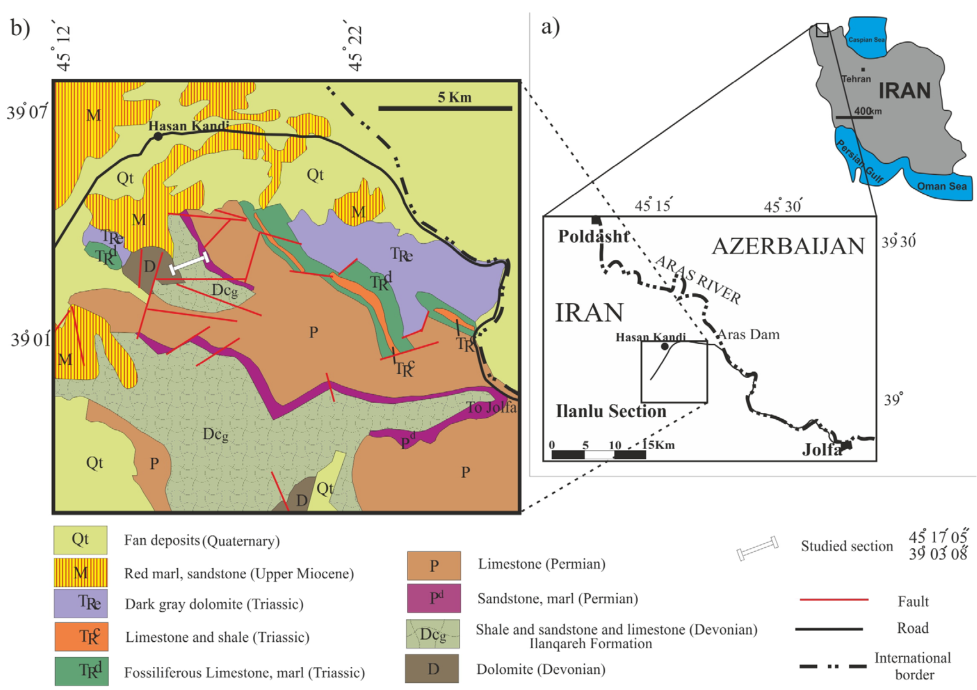

Figure 2 a) Location map of the studied section of Ilanqareh Formation in Azarbaijan Province of Northwestern Iran, b) Geological map of Ilanlu section (modified from Bolourchi and Saidi (1987)).

North Africa and Saudi Arabia were subjected to an intercontinental extension from Late Devonian to possibly Early Carboniferous, and the Arabian and adjacent plates were structurally affected by a regional Hercynian tectonic event (Husseini, 1991, 1992). The first study which showed the transgression of sandstone, conglomerate, and fossiliferous limestones of the Devonian Ilanqareh Formation over a Precambrian crystalline basement in the Azarbaijan region was carried out by Grewingk (1853). Rieben (1935) performed the first biostratigraphic studies on carbonate parts of the Ilanqareh Formation. The lower contact of Ilanqareh Formation is not over Precambrian crystalline basement in all parts of Azarbaijan area, and in some places, including the north of Tabriz, the transgression of Ilanqareh deposits is on Lower Palaeozoic sandstones of Lalun and Mila formations. Moreover, the deposits of this formation are overlain by the dolomites of the Ruteh Formation (Alavi-Naini and Bolourchi, 1973).

According to Alavi-Naini and Bolourchi (1973), Ilanqareh Formation can be stratigraphically divided into four members, including A) dolomite with interlayers of limestone and shale; B) thin-bedded fossiliferous limestone and shale; C) sandstone shale unit; and D) limestones related to the Lower Carboniferous.

The type section of the Ilanqareh Formation is located near Ilanqareh village in the area between Maku and the Aras River, but due to the folding and faulting in the region, lithostratigraphic units of the Ilanqareh Formation are not well defined in this area (Wendt *et al.*, 2005).

The present study has investigated an outcrop around the city of Jolfa and south of the Aras Dam (Northern Ilanlu village) called the Ilanlu section (Figure 2). The thickness of the Ilanqareh

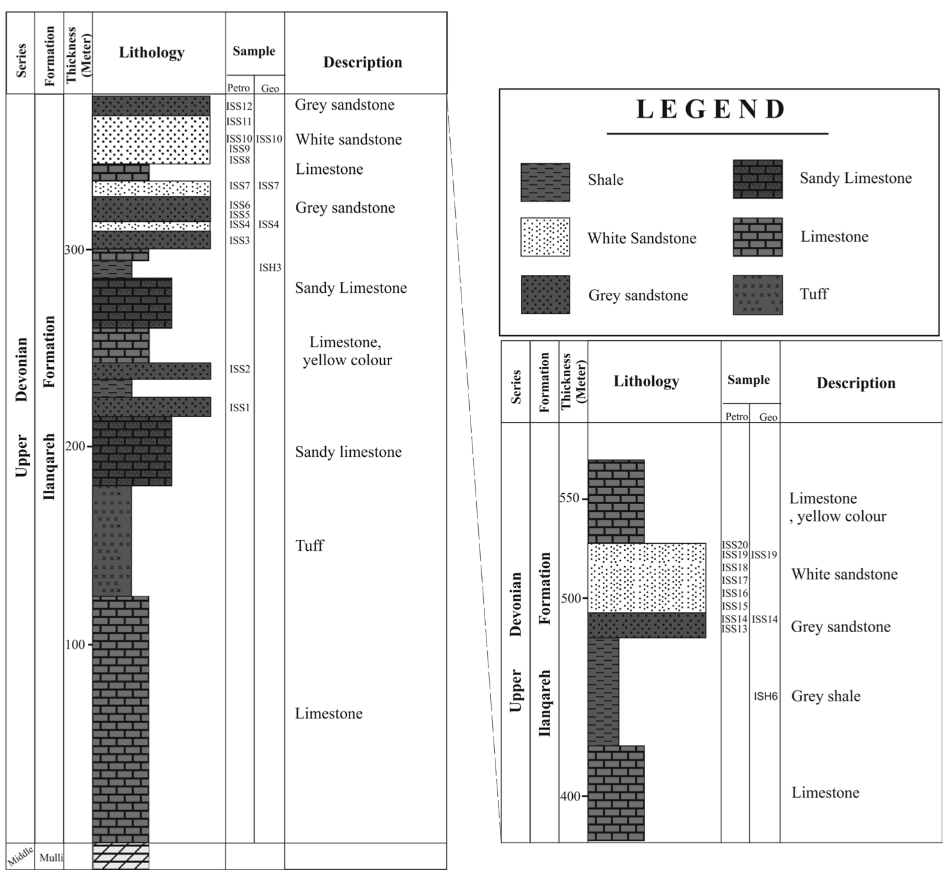

Figure 3 Lithostratigraphic column of Ilanqareh Formation in Ilanlu outcrop.

Formation in the Ilanlu section is 520 meters (Figure 3), and it is located over the dolomites of Mulli Formation, and the upper boundary contains Carboniferous limestones (Figures 4a and 4b).

The focus of this study is on sandstones and shales of member C of the formation. The sandstones of this member are often medium layered and have a parallel laminated sedimentary structure (Figure 4c). In some places, these sandstones are visible, along with the interlayers of highly fissile, micaceous reddish shale.

3. Methods and materials

A stratigraphic outcrop from the Ilanqareh Formation was measured and sampled at the Ilanlu section. Thirty representative fresh samples were selected for petrographic investigations. Among them, twenty medium-grained sandstone samples were selected for modal analysis. The amounts of detrital and diagenetic components were determined by counting 300 points in every 20 thin sections (Table 1). Point counting was done using the Gazzi-Dickinson method (Ingersoll *et al.*, 1984). Table 2 lists the recalculated modal compositions for the sandstones. Total abundances of the major oxides were reported on a 0.5g sample analyzed by ICP-emission spectrometry following a lithium metaborate/ tetraborate fusion and dilute nitric digestion at the laboratories of the ACME, Canada (Table 3). Weight difference after ignition at 1000°C used to determine Loss on ignition (LOI). For each element analyzed, the reproducibility of replicate analyses and the deviation from the certified values of the secondary standards are less than 5% relative.

4. Results

4.1. PETROGRAPHY

In terms of grain size, the studied sandstones were mostly fine to medium, and they were moderately to well-sorted. The petrographic composition of the Ilanqareh sandstones is listed in Table 1. The main components of these sandstones were quartz and potassium feldspar. In all samples, quartz

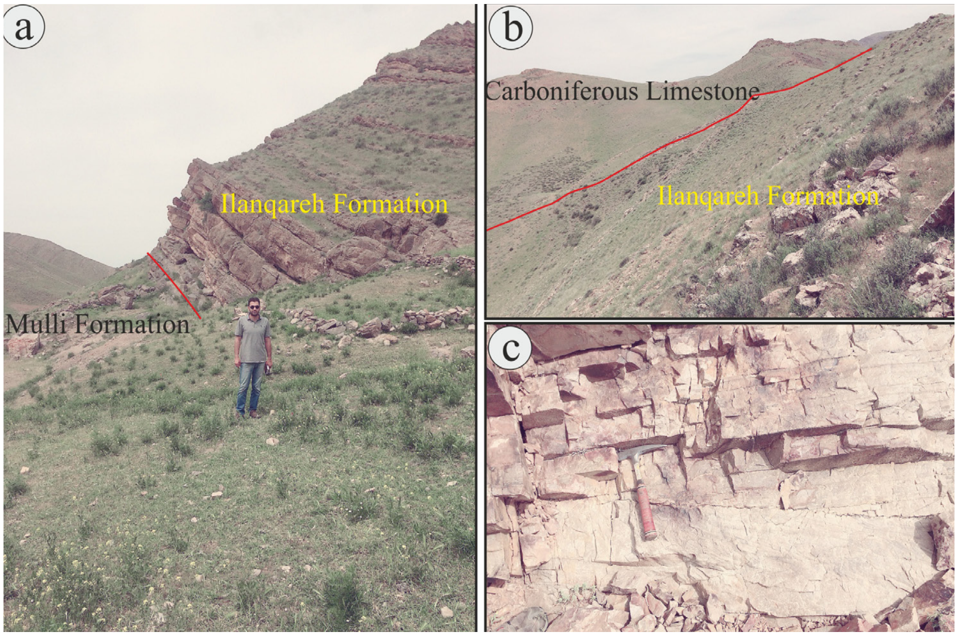

Figure 4 a) The lower boundary of Ilanqareh Formation with Mulli Formation, b) the upper contact of Ilanqareh Formation with Carboniferous limestones, c) medium layered sandstone with parallel lamination.

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Table 1. Point-counting results of the sandstones selected from the Ilanqareh Formation.

Sample no.	*Quartz*				*Feldspar*		*Rock Fragment*				*Cement*				Bio	Acc	Sum
	Monocrystal		Polycrystal														
	Nonundulatory	Undulatory	< or = 3 Crystal	> 3 Crystal	Kf	P	Cht	S	V	M	Cal	Fe Oxi	Silica	Clay			
IS1	95	39	0	3	6	0	0	0	0	0	98	35	10	5	29	12	332
IS2	109	42	0	5	8	0	0	0	0	0	89	39	5	5	0	9	311
IS3	99	39	0	2	5	0	0	0	0	0	101	11	8	0	22	15	302
IS4	149	73	0	10	13	0	0	0	0	0	10	45	35	14	0	9	358
IS5	89	44	0	6	5	0	0	0	0	0	115	15	5	16	0	8	303
IS6	148	75	0	8	10	0	0	0	0	0	55	12	9	17	0	11	345
IS7	159	85	0	9	11	0	0	0	0	0	9	10	33	21	0	12	349
IS8	152	76	0	8	12	0	0	0	0	0	12	12	45	15	0	5	337
IS9	149	81	0	7	10	0	0	0	0	0	10	12	47	21	0	14	351
IS10	139	79	0	5	9	0	0	0	0	0	0	5	32	25	0	12	306
IS11	143	91	0	6	11	0	0	0	0	0	0	12	39	26	0	9	337
IS12	151	89	0	4	9	0	0	0	0	0	0	15	41	35	0	12	356
IS13	142	89	0	11	15	0	0	0	0	0	0	15	45	14	0	9	340
IS14	149	96	0	9	8	0	0	0	0	0	0	10	39	12	0	11	334
IS15	146	101	0	8	12	0	0	0	0	0	0	5	42	5	0	8	327
IS16	151	98	0	5	9	0	0	0	0	0	0	0	51	17	0	15	346
IS17	144	87	0	7	9	0	0	0	0	0	5	45	39	13	0	11	360
IS18	145	91	0	8	12	0	0	0	0	0	0	33	38	12	0	13	352
IS19	147	94	0	6	11	0	0	0	0	0	0	21	41	22	0	9	351
IS20	141	103	0	7	9	0	0	0	0	0	0	35	39	17	0	14	365
Mean	137	79	0	7	10	0	0	0	0	0	25	19	32	16	3	11	338

Table 2. Recalculated compositions of the sandstones from the Ilanqareh Formation (in percent). Qm (monocrystalline quartz), F (total feldspar = K-feldspar + plagioclase), Lt (aphanitic lithic fragments + polycrystalline quartz), Qt (monocrystalline quartz + polycrystalline quartz + chert), F (total feldspar = K-feldspar + plagioclase), L (aphanitic lithic fragments), Q (total quartz = monocrystalline quartz + polycrystalline quartz), F (total feldspar = K-feldspar + plagioclase), R (aphanitic lithic fragments).

Sample	Qt F L (%)			Qm F Lt (%)			Q F Rf (%)		
	Qt	F	L	Qm	F	Lt	Q	F	Rf
IS1	95.8	4.2	0.0	93.7	4.2	2.1	95.8	4.2	0.0
IS2	95.1	4.9	0.0	92.1	4.9	3.0	95.1	4.9	0.0
IS3	96.6	3.4	0.0	95.2	3.4	1.4	96.6	3.4	0.0
IS4	94.7	5.3	0.0	90.6	5.3	4.1	94.7	5.3	0.0
IS5	96.5	3.5	0.0	92.4	3.5	4.2	96.5	3.5	0.0
IS6	95.9	4.1	0.0	92.5	4.1	3.3	95.9	4.1	0.0
IS7	95.8	4.2	0.0	92.4	4.2	3.4	95.8	4.2	0.0
IS8	95.2	4.8	0.0	91.9	4.8	3.2	95.2	4.8	0.0
IS9	96.0	4.0	0.0	93.1	4.0	2.8	96.0	4.0	0.0
IS10	96.1	3.9	0.0	94.0	3.9	2.2	96.1	3.9	0.0
IS11	95.6	4.4	0.0	93.2	4.4	2.4	95.6	4.4	0.0
IS12	96.4	3.6	0.0	94.9	3.6	1.6	96.4	3.6	0.0
IS13	94.2	5.8	0.0	89.9	5.8	4.3	94.2	5.8	0.0
IS14	96.9	3.1	0.0	93.5	3.1	3.4	96.9	3.1	0.0
IS15	95.5	4.5	0.0	92.5	4.5	3.0	95.5	4.5	0.0
IS16	96.6	3.4	0.0	94.7	3.4	1.9	96.6	3.4	0.0
IS17	96.4	3.6	0.0	93.5	3.6	2.8	96.4	3.6	0.0
IS18	95.3	4.7	0.0	92.2	4.7	3.1	95.3	4.7	0.0
IS19	95.7	4.3	0.0	93.4	4.3	2.3	95.7	4.3	0.0
IS20	96.5	3.5	0.0	93.8	3.5	2.7	96.5	3.5	0.0

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Table 3. The major element concentration of sandstone and shale samples of the Ilanqareh Formation.

Sample	IS4	IS7	IS10	IS14	IS19	ISH3	ISH6
	SS	SS	SS	SS	SS	SH	SH
SiO_2	89.54	93.05	89.24	97.04	90.03	53.88	56.22
Al_2O_3	4.81	2.99	5.37	1.53	4.5	25.59	27.78
Fe_2O_3	2.42	1.64	0.82	0.57	2.01	5.62	1.13
MgO	0.06	0.04	0.07	0.02	0.07	0.46	0.27
CaO	0.14	0.11	0.14	0.12	0.05	0.3	0.25
Na_2O	0.02	0.02	0.02	0.02	0.02	0.07	0.09
K_2O	0.41	0.71	1.25	0.3	0.83	1.97	1.98
TiO_2	0.35	0.19	0.85	0.07	0.45	1.11	1.37
P_2O_5	0.05	0.04	0.27	0.01	0.07	0.15	0.07
MnO	0.06	0.01	0.01	0.02	0.01	0.03	0.01
LOI	2.1	1.1	1.7	0.4	1.8	10.6	10.6
CIA	90.42	78.18	84.38	79.76	82.35	91.55	91.93
ICV	0.71	0.91	0.59	0.66	0.78	0.37	0.18

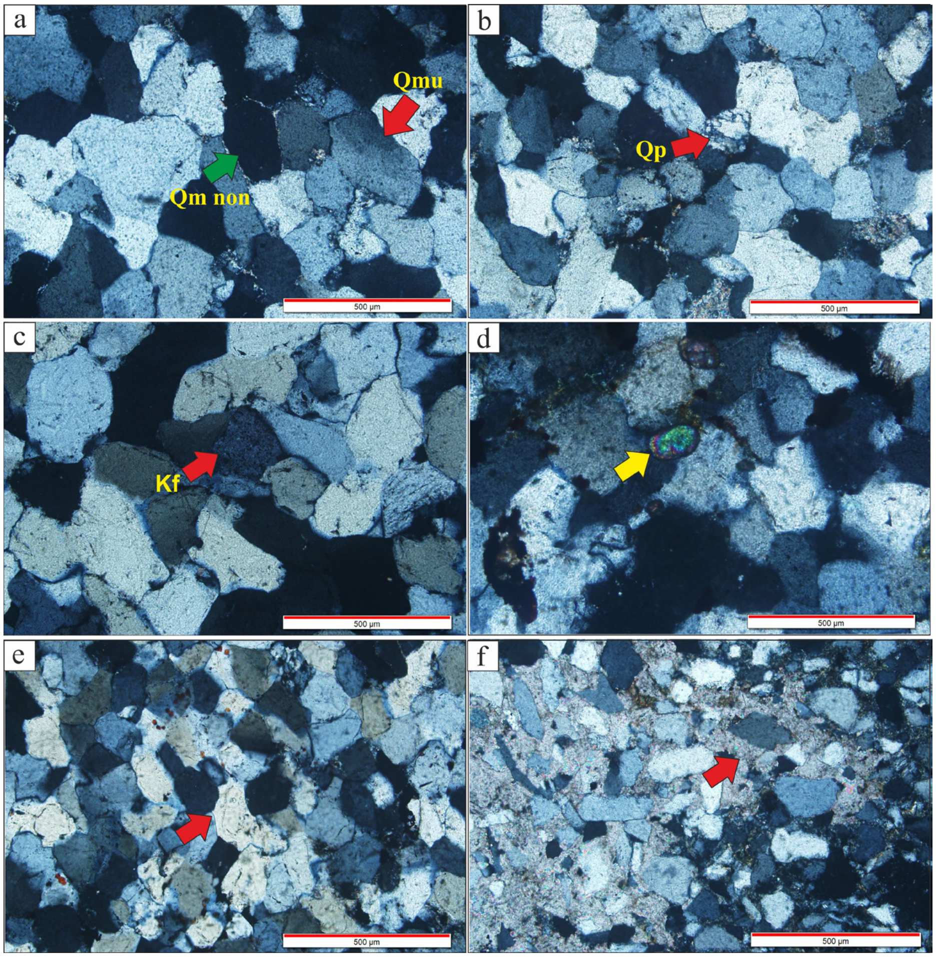

Figure 5 Selected thin-section photomicrographs of detrital grains of sandstones from the Ilanqareh Formation, (a) A photomicrograph showing monocrystalline quartz grains with slightly wavy extinction (red arrow) and straight extinction (green arrow), b) A polycrystalline quartz grain (red arrow) in a well-sorted sandstone, c) A K-feldspar grain (red arrow) between undulatory and nonundulatory extinction monocrystalline quartz grains, d) A very rounded zircon grain, e) Overgrowth quartz cements in a quartzarenite petrofacies, f) A carbonate-cemented medium-grained sandstone in the Ilanqareh Formation.

occurred with nonundulatory monocrystalline quartz being the dominant type and ranging from 29.3% to 45.5% (avg. 40.4%) in the Ilanlu section (Figure 5a). Undulatory extinction monocrystalline quartz (Figure 5a) ranged between 11.7% and 30.8% (avg. 23.0%). The polycrystalline (Figure 5b) quartz variety was a common form with an average of 1.9%. Feldspar occurred as K-feldspar (Figure 5c) ranging from 1.7% to 4.4% (avg. 2.8%). There were no lithic fragments in the Ilanqareh sandstones. Accessory minerals (avg. 3.2%) occurred in the form of muscovite and some heavy minerals, such as tourmaline and zircon (Figure 5d). Cements occurred in the most abundant forms of carbonate ranging from 0% to 38 % (avg. 15.5%), iron oxide ranging from 0% to 13 % (avg. 8.8%), silica ranging from 1% to 9 % (avg. 5.2%), and clay ranging from 0 % to 9 % (avg. 4%), respectively (Figures 5e and 5f). In order to classify the sandstones, their counted components were recalculated to 100%, excluding cements, matrix, and accessory components. Based on the average composition of the three main framework grain (Table 1), the composition of the sandstones was found to be quartzarenite and subarkose according to the Folk (1980) classification (Figure 6a) and quartzose based on the Garzanti (2016) classification (Figure 6b). Plotting the point-counting data of the Ilanqareh Formation on the diagram of ratio of total quartz on total feldspar plus rock fragments (Qt/F+RF) against polycrystalline quartz and chert on feldspar plus rock fragments (Suttner and Dutta,1986) indicated the existence of a humid climate (Figure 7). Based on recalculated compositions of the sandstone's modal analysis (Qm-F-Lt and Qt-F-L; table 2), all the studied samples fell into the craton interior field (Figures 8a - 8b).

4.2. GEOCHEMISTRY

Table 3 presents the major element concentrations of the analyzed sandstone (N=5) and shale (N=2) samples. The SiO_2 content of the sandstone samples ranged from 89.24% to 97.04% (avg. 91.78 wt%), while shale samples had SiO_2 content of 53.78 wt% to 56.22 wt%. The sandstones were also characterized by low content of Al_2O_3 (1.53-5.37 wt%), CaO (0.05-0.14 wt%), TiO_2 (0.07-0.85 wt%), Fe_2O_3 (0.57-2.42 wt%), and K_2O (0.3-1.25 wt%). These major oxides also had very low values in the shale samples except for the Al_2O_3, which varied from 25.59 wt% to 27.78 wt%. The major oxides of sandstones were examined based on bivariate diagrams against Al_2O_3. Accordingly, Al_2O_3 and SiO_2 showed a negative correlation (Figure 9a). Among the other oxides, MgO, CaO, and TiO_2 showed strong positive correlations with

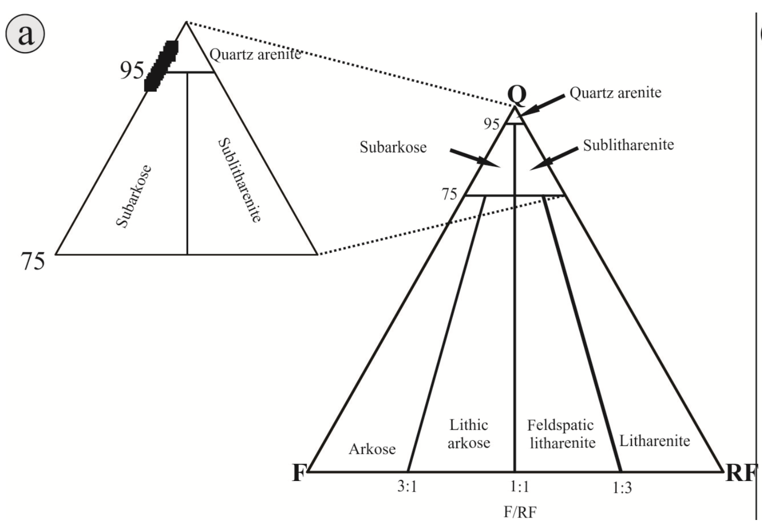

Figure 6 Classification of the sandstones from the Ilanqareh Formation: a) QFR triangle diagram of Folk (1980), b) QFR triangle diagram of Garzanti (2016).

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Al_2O_3 (Figures 9b-9d). On the K_2O against Al_2O_3 (Figure 9e), all samples lay below the K_2O/Al_2O_3 ratio of 0.3 (dotted line), which indicated that most of the K_2O were inside the clay fractions ($K_2O/Al_2O_3 < 0.3$) and not in the potassium feldspars ($0.3 < K_2O/Al_2O_3 < 0.9$, according to Cox *et al.* (1995)). Among the other oxides, Fe_2O_3 showed a weak positive correlation with Al_2O_3 (Figure 9f), and the remaining major oxides (MnO and Na_2O, not illustrated in Figure 9) indicated a low correlation with Al_2O_3.

In order to determine the degree of weathering of sediments, different indices have been suggested based on the molecular ratios of various oxides of different elements, especially mobile ones (MgO, CaO, K_2O, and Na_2O), relative to immobile elements and oxides, such as ZrO_2, Al_2O_3, and TiO_2 (Parker 1970; Nesbitt and Young, 1982; Fedo *et al.*, 1995; Nesbitt *et al.*, 1996; Scheffler *et al.*, 2006). One of the most important criteria for determining the intensity of chemical weathering is the chemical index of alteration (CIA) (Nesbitt and Young, 1982). The CIA is expressed as $Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O) \times 100$, where all the oxides are in molecular proportion and CaO* represents Ca in silicate minerals. (Nesbitt and Young, 1982). The studied sandstone and shale samples had CIA values of 78.18 to 90.42 and 91.55 to 91.93, respectively (Table 3). The climatic condition of the source areas of siliciclastic sediments can also be determined based on the diagram of SiO_2 versus (Al_2O_3+K_2O+Na_2O) (Suttner and Dutta, 1986) (Figure 10), in which samples of the Ilanqareh Formation were plotted in the humid climate range.

The Index of Compositional Variability (ICV; Cox *et al.*, 1995) expressed as $ICV = (Fe_2O_3 + K_2O + Na_2O + CaO + MgO + MnO + TiO_2)/Al_2O_3$ can be used to measure the degree of the recycling and compositional maturity of siliciclastic sedimentary rocks. As can be seen in Table 3, the sandstones and shales of the Ilanqareh Formation had ICVs of 0.59-0.91 and 0.18-0.37, respectively.

In K_2O/Na_2O versus SiO_2 diagram proposed by Roser and Korsch (1986), the data from studied samples fell into a passive margin tectonic setting (Figure 11a). By using the new major element discrimination function diagrams of Verma and Armstrong-Altrin (2013) all the studied sandstones (except sample IS14 with $(SiO_2)_{Adj}$ >95 %) and one shale sample (ISH6) were completely in the rift field of the high-silica diagram, and one shale sample (ISH3) fell into the collision range using the low-silica diagram (Figures 11b and 11c).

5. Discussion

5.1 PALEOWEATHERING

The intensity of chemical weathering is a function of the climate and tectonic activity. Lower tectonic activity and higher humidity in the source region result in more intense chemical weathering. The use of point-count data and whole rock geochemical data can help in assessing the paleo-climate condition of siliciclastic sediments (Suttner and Dutta, 1986). The ratio of Qt/F+RF against Qp/F+RF (Figure 7), also the high amount of SiO_2 in contrast to the low amount of Al_2O_3, K_2O and Na_2O (Figure 10) in studied sandstones indicated

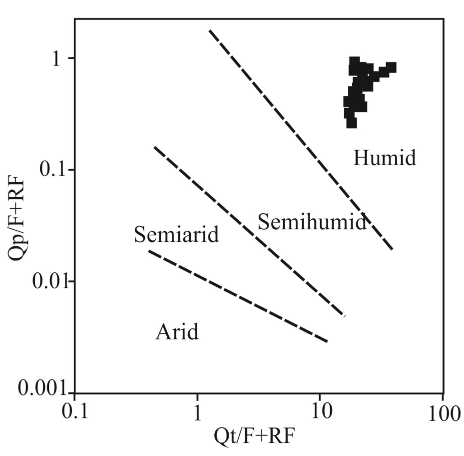

Figure 7 The point-counting data of sandstones from the Ilanqareh Formation on the Suttner and Dutta (1986) diagram (Qt =monocrystalline quartz + polycrystalline quartz + chert; Qp= polycrystalline quartz + chert); (F =total feldspar); (Rf =total rock fragments).

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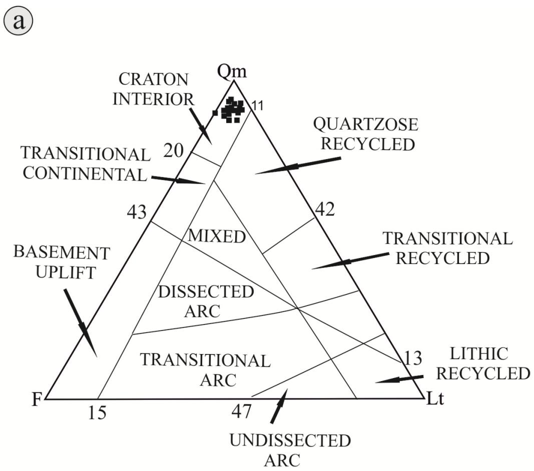

Figure 8 a) QmFLt and b) QtFL ternary diagram (after Dickinson et al., 1983) for the studied sandstone and shale samples of the Ilanqareh Formation.

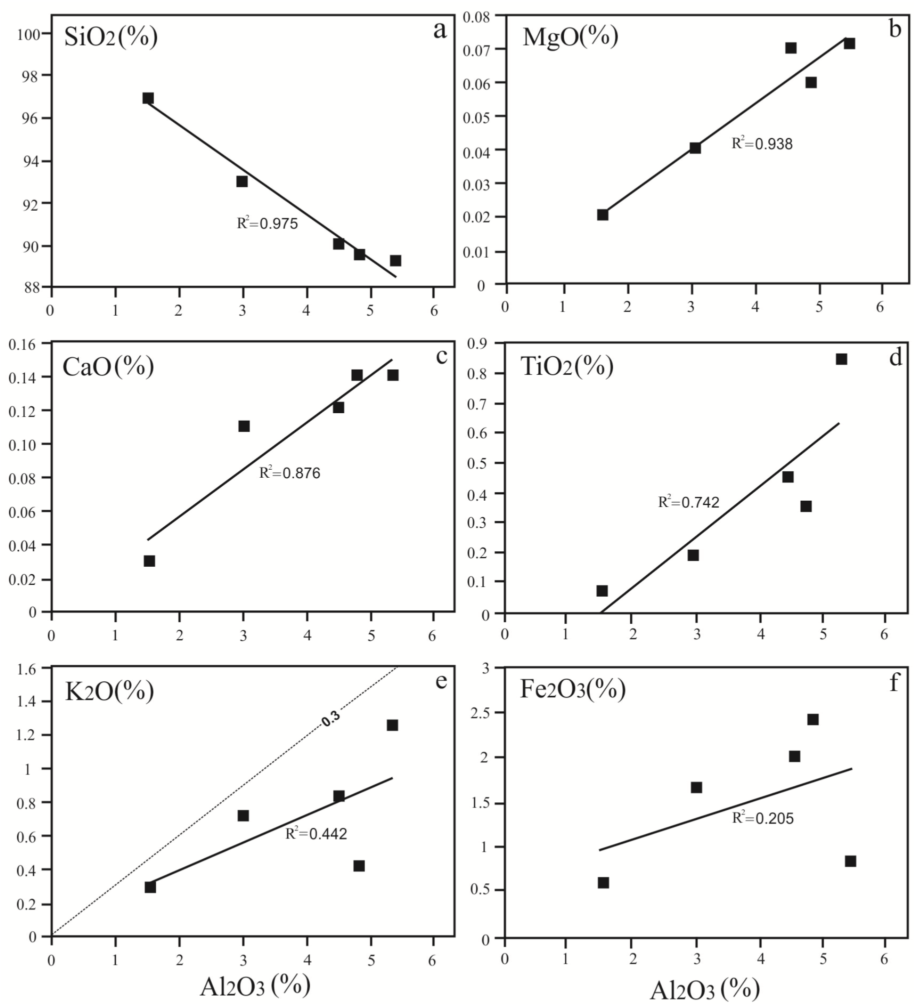

Figure 9 Selected major oxide, Al_2O_3, bivariate diagrams for sandstones of the Ilanqareh Formation.

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that the degree of chemical weathering in the source areas of these sediments was moderate to high, which is confirmed by the values of the chemical index of alteration calculated for the studied sandstone and shale samples (Table3). The paleogeographic maps presented by Bagheri and Stampfli (2008) also show that the region of Azarbaijan was located above 30 degrees south latitudes during the early Devonian to the early and middle Permian and according to Zhuravlev and Sokiran (2020), this region was located in a temperate climate during the Late Devonian.

5.2. EFFECT OF RECYCLING

Although in petrographic studies no evidence of sedimentary recycling such as sedimentary rock fragments and chert has been seen, nevertheless, geochemical studies assured the effect of sedimentary recycling in these sandstones. Samples with ICVs above 1 are usually first cycle and immature sediments, whereas those with ICVs below 1 are highly mature (recycled). As can be seen in table 3, the sandstones and shales of the Ilanqareh Formation show ICVs below 1, indicating that they were not the first cycle sediments. Similar results have been also observed in studies on Devonian deposits in other parts of Iran, including Alborz (Hosseini *et al.*, 2019; Jafarzadeh *et al.*, 2021; Bónová *et al.*, 2021a, 2021b) and Central Iran (Zand-Moghadam *et al.*, 2013) and Zagros (Zoleikhaei *et al.*, 2015). The existence of sedimentary recycling in the supply of sediments of the Ilanqareh Formation has been corroborated, especially by studying the heavy minerals (highly rounded zircon, tourmaline, and rutile and high ZTR index) in these sandstones (Bónová *et al.*, 2021a, 2021b). Nevertheless, the increase of ultrastable heavy minerals, in addition to being the result of recycling, can also be related to intense weathering and long transport during sedimentation (Bassis *et al.*, 2016).

5.3. TECTONIC SETTING

The results of sandstone modal analysis based on three main components (Qm-F-Lt and Qt-F-L) can provide important information about the types of the main provenance, such as the cratons' interior, recycled orogens, basement uplifts, and magmatic arcs (Dickinson and Suczek, 1979; Dickinson *et al.*, 1983). According to the petrographic studies and point count analysis performed in this study using the QmFLt and QtFL diagrams of Dickinson *et al.*, (1983), the studied samples were plotted in the fields of stable cratons (Figure 8), which generally reflected very mature sandstones derived from areas of low lying granitoid or gneiss sources (Dickinson *et al.*, 1983). Therefore, it seems that the entry of sediments from the source of stable craton can be considered the main source for the sediments of the Ilanqareh Formation. The relationship between siliciclastic whole-rock geochemistry and plate tectonic of source areas has been explored by many sedimentologists and geochemists (Bhatia, 1983; McLennan *et al.*, 1990; Kumon and Kiminami, 1994; Verma and Armstrong-Altrin, 2013). Whole rock geochemical data such as K_2O/Na_2O versus SiO_2 diagram (Figure 11a) proposed by Roser and Korsch (1986) and major element discrimination function diagrams of Verma and Armstrong-Altrin (2013) (Figures 11b-11c) also avouched the existence of a rift which is consisted with passive margin (Verma *et al.*, 2016) tectonic setting for the studied samples.

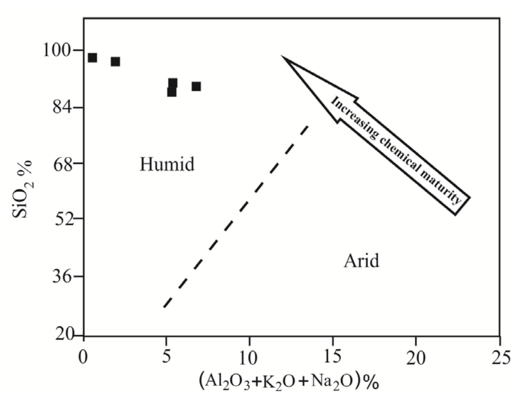

Figure 10 Bivariate diagram of SiO_2 wt.% versus (Al_2O_3+K_2O+Na_2O) wt. % (after Suttner and Dutta, 1986) for sandstones of the Ilanqareh Formation.

5.4. PALEOGEOGRAPHIC IMPLICATION

The land of Iran and the region of Azarbaijan, along with the plate of Turkey and the largest part of the Middle East continents, are located on the passive northwestern margin of the Gondwana supercontinent and are connected to the African-Arabian plate on the southern edge of the Paleo-Tethys Ocean on the width of about 30 degrees south. The paleogeographic location of Iran in the Paleozoic (Stampfli and Borel, 2003), the abundance of Neoproterozoic-Early Cambrian (Cadomian) granites in Iran and other regions such as Thurides and Iberia (Moghaddam *et al.*, 2017) and recent studies in different regions of Iran's sedimentary-structural zones on the Devonian deposits (Aharipour *et al.*, 2010; Zand-Moghadam *et al.*, 2013) have confirmed this issue. Considering the conjunction of these plates in the northern margin of the Gondwana supercontinent in the Devonian period and according to the paleogeography of the study area in that period, Arabian Craton can be considered the main source for direct entry of sediments into the sedimentary basin of the Ilanqareh Formation in Devonian. Recycling and erosion of sediments of the Lower Palaeozoic age which also derived their sediments from the Arabian Craton can be considered a secondary source for the entry of sediments into the sedimentary basin of the

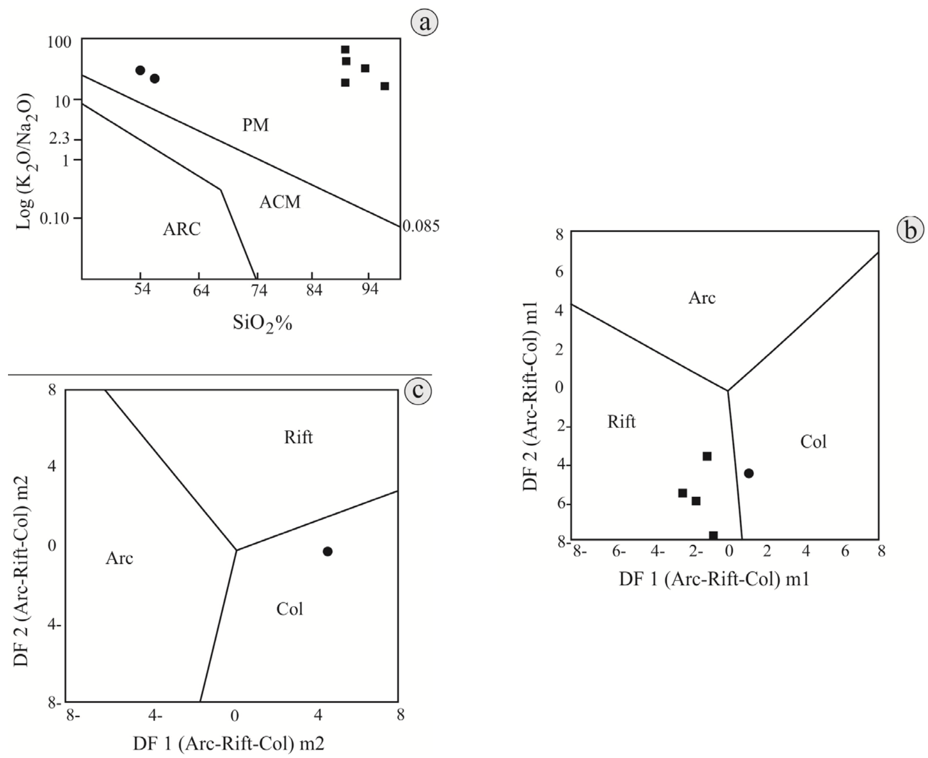

Figure 11 a)Tectonic discrimination function diagrams of Roser and Korsch (1986); b) tectonic multi-element discrimination diagram proposed by Verma and Armstrong-Altrin (2013) for low silica samples; DF1(Arc-Rift-Col)m2 = (0.608 × ln(TiO$_2$/SiO$_2$)$_{adj}$) + (−1.854 × ln(Al$_2$O$_3$/SiO$_2$)$_{adj}$) + (0.299 × ln(Fe$_2$O$_3$t/SiO2)$_{adj}$) + (−0.550 × ln(MnO/SiO$_2$)$_{adj}$) + (0.120 × ln(MgO/SiO$_2$)$_{adj}$) + (0.194 × ln(CaO/SiO$_2$)$_{adj}$) +(−1.510 × ln(Na$_2$O/SiO$_2$)$_{adj}$) + (1.941 × ln(K$_2$O/SiO$_2$)$_{adj}$) + (0.003 × ln(P$_2$O$_5$/SiO$_2$)$_{adj}$) − 0.294. DF2(Arc-Rit-Col)m2 = (−0.554 × ln(TiO$_2$/SiO$_2$)$_{adj}$) + (−0.995 × ln (Al$_2$O$_3$/SiO$_2$)$_{adj}$) + (1.765 × ln(Fe$_2$O$_3$t/SiO$_2$)$_{adj}$) + (−1.391 × ln(MnO/SiO$_2$)$_{adj}$) + (−1.034 × ln(MgO/SiO$_2$)$_{adj}$) + (0.225 × ln(CaO/SiO$_2$)$_{adj}$) + (0.713 × ln(Na$_2$O/SiO$_2$)$_{adj}$) + (0.330 ×ln(K$_2$O/SiO$_2$)$_{adj}$) + (0.637 × ln(P$_2$O$_5$/SiO$_2$)$_{adj}$) − 3.631; c) for high silica samples; DF1(Arc-Rift-Col)m1 = (−0.263 × ln(TiO$_2$/SiO$_2$)$_{adj}$) + (0.604 × ln (Al$_2$O$_3$/SiO$_2$)$_{adj}$) + (−1.725 × ln(Fe$_2$O$_3$t/SiO$_2$)$_{adj}$) + (0.660 × ln(MnO/SiO$_2$)$_{adj}$) + (2.191 × ln(MgO/SiO$_2$)$_{adj}$) + (0.144 × ln(CaO/SiO$_2$)$_{adj}$) + (−1.304 × ln(Na$_2$O/SiO$_2$)$_{adj}$) +(0.054 × ln(K$_2$O/SiO$_2$)$_{adj}$) + (−0.330 × ln(P$_2$O$_5$/SiO$_2$)$_{adj}$) + 1.588. DF2(Arc-Rit-Col) m1= (−1.196 × ln(TiO$_2$/SiO$_2$)$_{adj}$)+(1.604 × ln(Al$_2$O$_3$/SiO$_2$)$_{adj}$)+(0.303 × ln(Fe$_2$O$_3$t/SiO$_2$)$_{adj}$)+(0.436 × ln(MnO/SiO$_2$)$_{adj}$)+(0.838 × ln(MgO/SiO$_2$)$_{adj}$)+(−0.407 × ln(CaO/SiO$_2$)$_{adj}$)+ (1.021 × ln(Na$_2$O/SiO$_2$)$_{adj}$)+(−1.706 × ln(K$_2$O/SiO$_2$)$_{adj}$)+(−0.126 × ln(P$_2$O$_5$/SiO$_2$)$_{adj}$) − 1.068; (A: oceanic island arc; B: continental island arc; C: active continental margin; D: passive continental margin).

Ilanqareh Formation. Most of the sandstones studied in different regions of the Middle East and different parts of Iran indicate the predominant composition of quartz arenite and felsic parent rocks associated with the Arabian Craton (Zand-Moghadam *et al.*, 2013; Zoleikhaei *et al.*, 2015; Bassis *et al.*, 2016).

6. Conclusion

1. The investigation of the Ilanqareh Formation sandstones reveals quartzarenite and subarkose as the main sandstone types.
2. The late Devonian in the northern margin of the Gondwana belonged to humid paleoclimate based on point counting and geochemical data.
3. It can be comprehensively inferred that the tectonic setting of provenance areas of the Upper Devonian Ilanqareh sediment was mainly related to the passive continental margin.
4. The entry of sediments from the source of stable craton can be considered the main source for the sediments of the Ilanqareh Formation and recycling of older sedimentary rocks could be another source of these sediments.
5. Considering the conjunction of blocks of Iran, Alborz, and Azarbaijan in the northern margin of the Gondwana during the Devonian, Arabian Craton could be the main source for the sediments entering the Ilanqareh Basin.

Contributions of authors

Javad Anjerdi: Resources, investigation, and writing original draft preparation; *Mahdi Jafarzadeh*: Conceptualization, methodology, investigation, validation, writing original draft preparation, reviewing and editing; *Adel Najafzadeh*: Investigation, visualisation and writing; *Rahim Mahari*: Investigation and validation.

Financing

This work was supported by the Islamic Azad University, Tabriz Branch.

Acknowledgments

We would like to thank all reviewers for their constructive critiques.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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