Provenance and tectonic setting of Upper Devonian sandstones from Ilanqareh Formation (NW Iran)

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ABSTRACT

Provenance and tectonic setting of the Upper Devonian sandstones in NW Iran have been interpreted on the basis of petrography and trace-element analysis of samples from two different stratigraphic sections. Modal analysis data of 27 samples with medium sand size and well-sorted properties from Ilanlu section and 23 samples from Ilanqareh section reveal that monocrystalline and polycrystalline (average 6% for Ilanlu section and 3% for Ilanqareh section) quartz grains with inclusions, such as rutile needle and apatite, can be derived from felsic igneous rocks of a craton interior setting. Geochemically, trace-element concentrations, such as La, Th, Sc and Zr, and ratios, such as La/Sc, Th/Sc, La/Co, and Th/Co, of sandstones from Ilanqareh Formation at both localities indicate felsic igneous source rocks and a passive continental margin setting for the source area. Furthermore, the evidence of recycling (for example, well rounded zircons) in the studied samples indicates that recycled sedimentary rocks should also be considered as one of the major source rocks. Enrichment in Zr, negative Sr anomalies and Th/U ratios higher than 3.8 for these sandstones are further evidence for recycled sources, which can be related to the effect of the Hercynian orogeny in NW Iran.

Key words: provenance, geochemistry, tectonic setting, Devonian, Ilanqareh Formation, Azarbaijan, Iran.

RESUMEN

La proveniencia y el ambiente tectónico de areniscas del Devoniano Superior del SW de Irán se interpretan en este trabajo con base en análisis petrográficos y de elementos traza de muestras de dos secciones estratigráficas. Los datos del análisis modal de 27 muestras de la sección Ilanlu, con tamaño de grano de arena media y buena clasificación, y de 23 muestras de la sección Ilanqareh, revelan que granos de cuarzo monocristalino y policristalino, los cuales contienen inclusiones, tales como agujas de rutilo y apatito, pudieron haberse derivado de rocas ígneas félsicas del interior de un cratón. La abundancia de elementos traza como La, Th, Sc y Zr y las relaciones La/Sc, Th/Sc, La/Co, and Th/Co en areniscas de la Formación Ilanqareh en las dos localidades indican rocas fuente de tipo ígneo félsico y un ambiente de margen continental pasivo para el área fuente. Además, la evidencia de reciclaje (por ejemplo, circones bien redondeados) en las muestras estudiadas indica que rocas sedimentarias recicladas deben ser también consideradas como una de las principales rocas funete. El enriquecimiento de Zr, anomalías negativas de Sr y valores de Th/U mayores que 3.8 en esas areniscas son evidencia adicional de fuentes recicladas, las cuales pueden estar relacionadas al efecto de la orogenia Herciniana en el NE de Irán.

Palabras clave: proveniencia, geoquímica, ambiente tectónico, Devoniano, Ilanqareh Formation, Azarbaijan, Iran.

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INTRODUCTION

Several models are commonly used to deduce provenance parameters (source rock lithology, climate, weathering, transport, and geotectonic setting) from petrographic analysis on sandstone framework (*e.g.*, Dickinson, 1985; Le Pera and Arribas, 2004). Also, during the last two decades, the use of geochemical data for provenance inferences has been significantly developed (see, *e.g.*, McLennan, 2001; Armstrong-Altrin *et al.,* 2004; Gabo *et al.,* 2009). Recent investigations on geochemical characteristics of ancient and modern detritus sediments have been carried out in order to infer the source rocks, provenance and tectonic setting (Gu *et al.,* 2002; Nesbitt and Young, 1996; Whitmore *et al.,* 2004; Bhatia, 1983; Roser *et al.,* 2002; Yan *et al.,* 2006), although caution is required in their indiscriminate use (Armstrong-Altrin and Verma, 2005). Trace elements (*e.g.*, Nb, Ni, V, Co, Y, La, Th, Sc and Zr) in clastic sedimentary rocks are considered to be immobile under conditions of weathering, diagenesis and moderate levels of metamorphism, and are commonly preserved in sedimentary rocks (Bhatia and Crook, 1986; McLennan *et al.,* 1993). Therefore, such trace elements might constitute well-established provenance and tectonic setting indicators (*e.g.*, Bhatia and Crook, 1986, Armstrong-Altrin, 2009).

Since most of petroleum reservoirs in Iran are hosted in carbonate rocks (Vaziri-Moghaddam *et al.,* 2010; Kavoosi *et al.,* 2009) less attention has been paid to the siliciclastic sediments, especially in relation to provenance studies. A few provenance studies, based on petrography and geochemistry of sandstones, have been carried out. For example, Jafarzadeh and Hosseini-Barzi (2008) used petrography and major-element geochemistry to evaluate provenance, tectonic setting and paleoweathering conditions of Ahwaz Sandstone Member of the Asmari Formation (Oligo-Miocene) in southwest Iran. In the present study, we used the petrographic and geochemical (trace-element) methods to interpret the provenance and tectonic setting of the Upper Devonian sandstones from Ilanqareh Formation at Ilanlu and Ilanqareh sections in Azarbaijan Province, NW Iran (Figure 1).

REGIONAL GEOLOGIC SETTING

In 1853, Grewingk, for the first time, reported the presence of Palaeozoic rocks in northwestern Iran. He

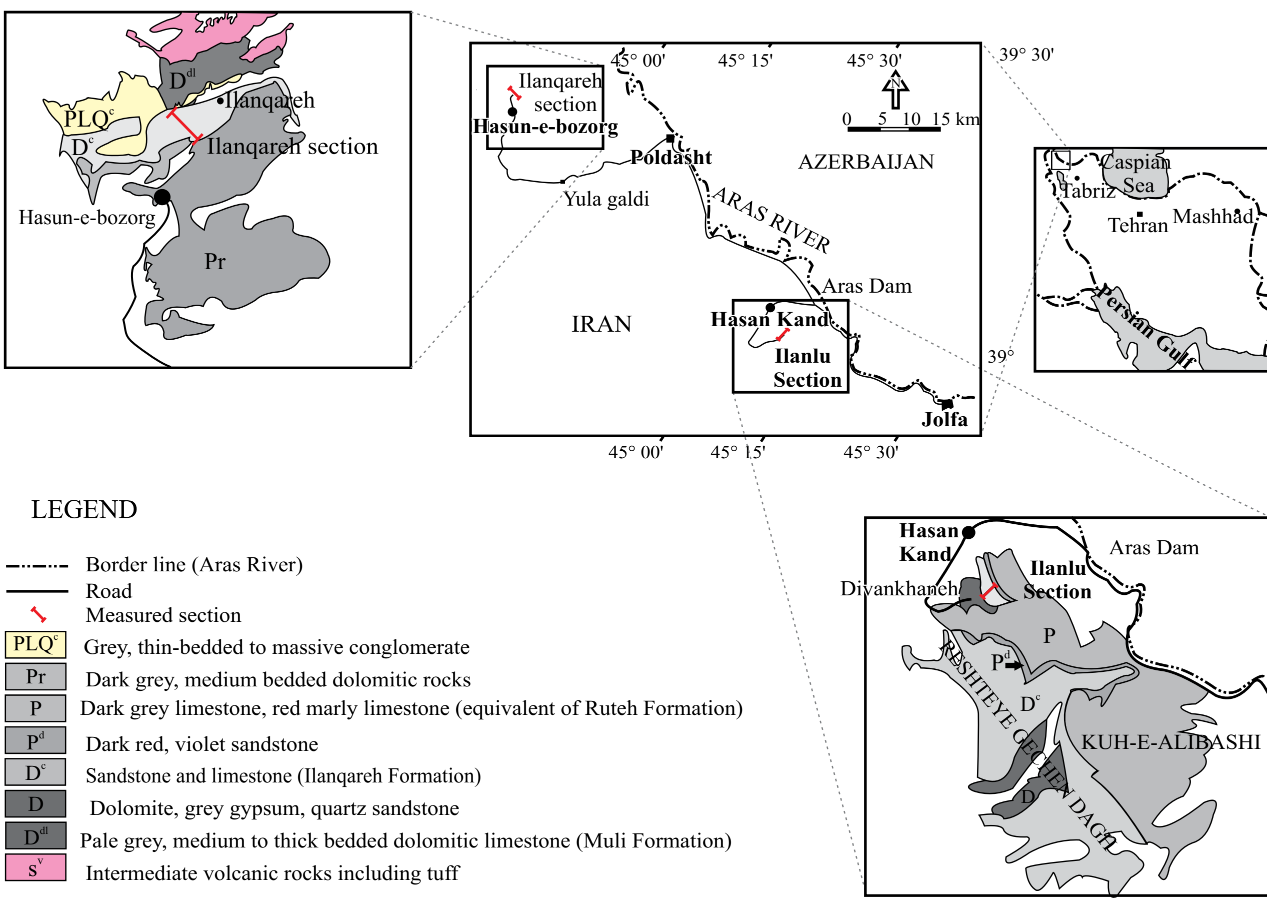

Figure 1. Location map of Ilanlu and Ilanqareh sections in the northwest Iran. The study area is located in the Azarbaijan Province of Iran, modified from Bolourchi and Saidi (1989).

stated that these sedimentary rocks, such as sandstones, conglomerates and fossiliferous limestones, are Devonian in age and transgressed over a crystalline basement. More information can be found in Frech and Arthaber (1900) report on the same region. The first biostratigraphic data were given by Rieben (1935) about the geology of the Iran-Azerbaijan borderland.

Alavi-Naini and Bolourchi (1973) reported that in the area north of Tabriz, sedimentary rocks are presumably of Early to Late Devonian in age (Muli and Ilanqareh Formations) that have transgressed on a Precambrian basement or on Lower Paleozoic sandstones and dolomites of the Lalun and Mila Formations and are in turn overlain by Permian platform dolomites of the Ruteh Formation. The Ilanqareh Formation in the study area conformably overlies the Muli Formation and underlies Jeirud (Devonian) or Ruteh (Permian) Formations.

Paleogeographic investigations indicate that at the time of deposition of Ilanqareh Formation (Devonian age), the northwest Iran was a part of the long and wide northern passive margin of Gondwanaland bordering the Paleo-Tethys Ocean (Sengor, 1990; Beydoun, 1991). Stump *et al.,* (1995) indicated that the Late Devonian to Early Carboniferous sediments are not uniformly distributed across the Arabian Peninsula due to uplift and erosion associated with the Hercynian Orogeny during the end of Devonian to Carboniferous. Also, regional comparison between Ilanqareh Formation of northwest Iran with the Upper Paleozoic formations in Syria, Iraq, Turkey and Saudi Arabia by Husseini (1991) indicates that during the Paleozoic times, North Africa and Arabia were part of a broad continental shelf margin and, furthermore, these areas were subjected to major intra-continental extension from Late Devonian to possibly Early Carboniferous and the Arabian and adjacent plates were structurally affected by a regional Hercynian tectonic event (Figure 2).

Based on stratigraphic characteristics, Alavi-Naini and Bolourchi (1973) divided this formation into four parts in ascending order: Part A: mainly composed of dolomite with interbeds of limestone and shale. Part B: consists of fossil bearing thin-bedded limestone and shale. Part C: mainly shale and sandstone. Part D: composed of the Lower Carboniferous limestones.

A much better and almost complete section through the upper part of the Muli and the entire Ilanqareh Formations is exposed near the village of Illanlu (Bolourchi and Saidi, 1989). The study area (The Ilanlu and Ilanqareh sections) is located in the northwest Iran, Azarbaijan Province. The Ilanlu section is located at south of the Aras Dam (Northern Ilanlu village) with thickness of 510 m and the Ilanqareh section is located in northwest of Poldasht (western Ilanqareh village) (Figure 1), and also the Ilanqareh Formation is about 320 m at this locality.

ANALYTICAL METHODS

As stated above, two stratigraphic sections of the Ilanqareh Formation were measured and sampled at Ilanlu and Ilanqareh locations (Figures 2 and 3). Fifty representative fresh outcrop samples were selected for petrographic studies.

The selected samples were mainly well-sorted and unweathered, fine- to medium grained, sand-size. Framework mineral composition (modal analysis) was quantified using the point-counting method of Gazzi-Dickinson as described by Ingersoll *et al.* (1984). Classification of grain types was done using the Dickinson (1985) method (Table 1).

Framework grains were counted for 250 to 300 counts per thin section. Modal analysis data from point counting of the framework grains and the recalculated sandstone compositions of the Ilanqareh sandstones are shown in

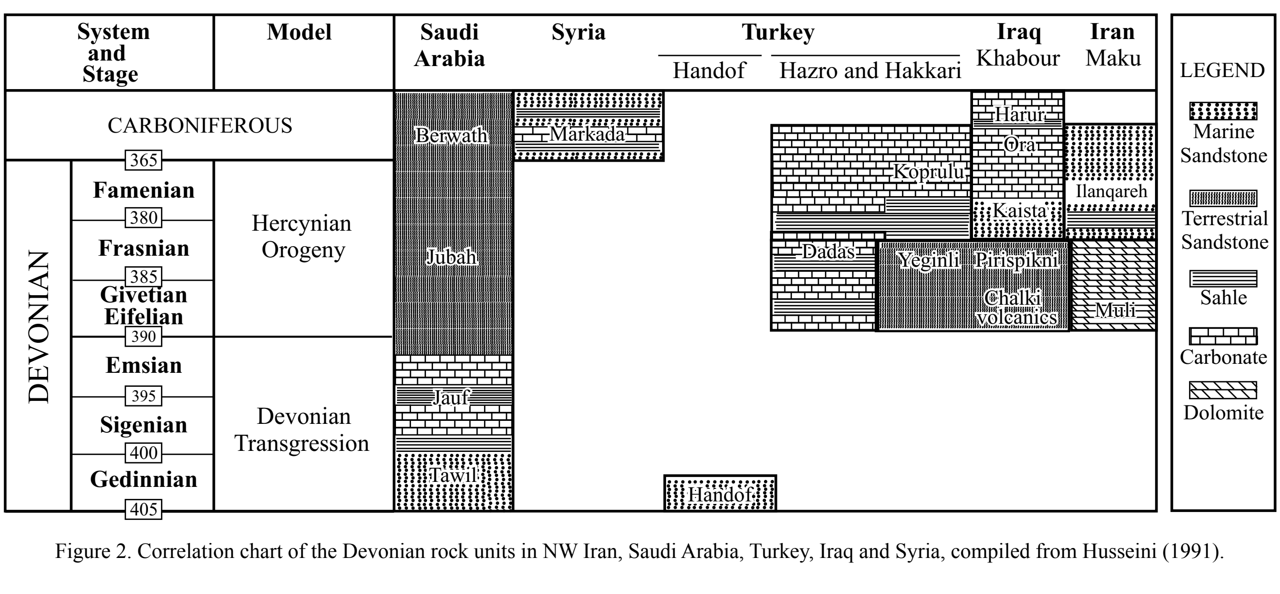

Figure 2. Correlation chart of the Devonian rock units in NW Iran, Saudi Arabia, Turkey, Iraq and Syria, compiled from Husseini (1991).

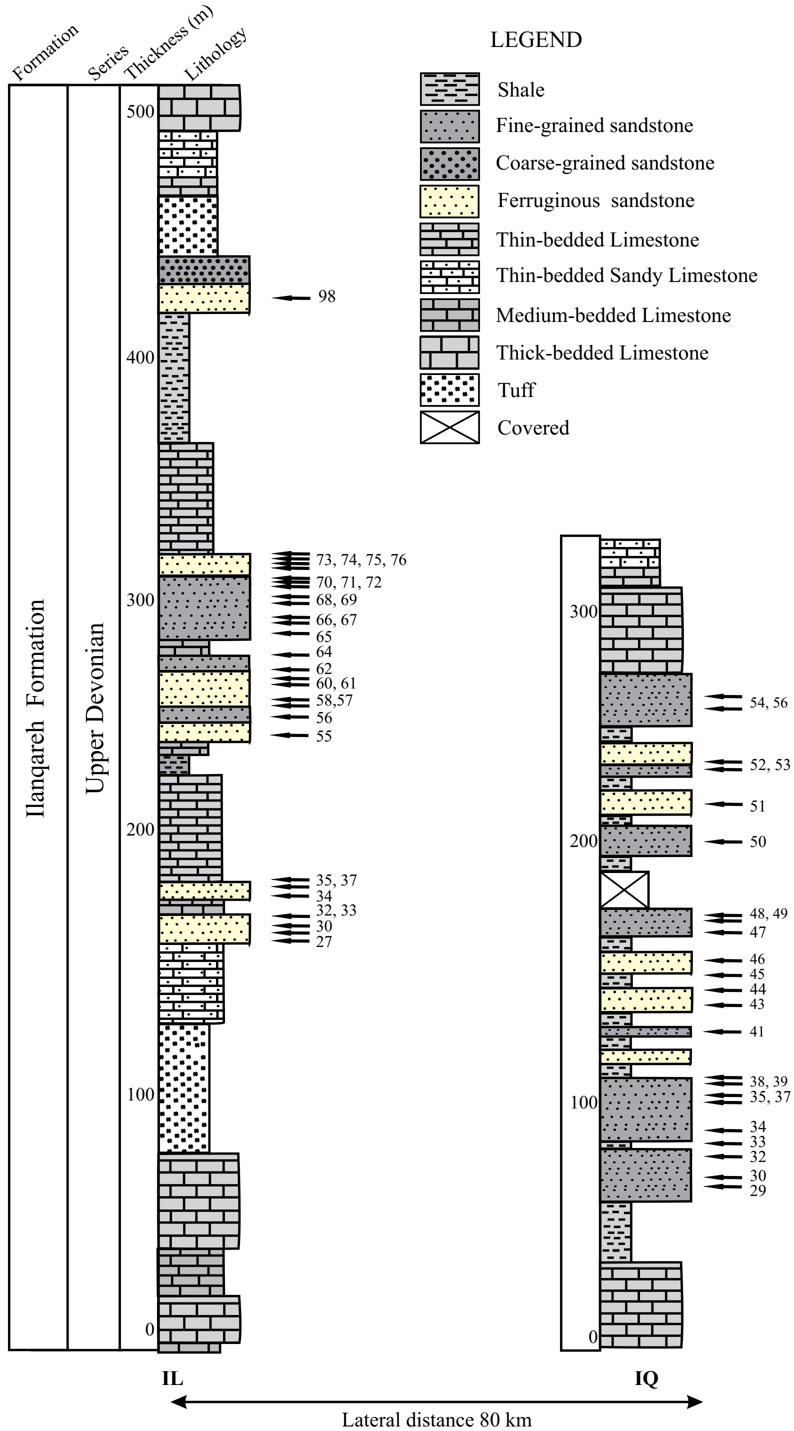

Figure 3. Lithostratigraphic columnar sections of the Upper Devonian Sandstones at Ilanlu and Ilanqareh. IL: Ilanlu section and IQ: Ilanqareh section (see Figure 1 for location of the sections).

Tables 1 and 2.

Trace-element analysis (12 samples from Ilanlu section and 10 samples from Ilanqareh section) was done by ICP-AES at the laboratories of the Geological Survey of Iran (Table 3). Accuracy and precision were estimated and monitored from the control samples. Detection limits (DL) for the elements were (in ppm): 10 for Ba, 1 for Rb, Co, Zr, Hf, Sr, Pb and V, 0.1 for Nb and Sc, 0.8 for Cr, 0.3 for La and Th, 0.4 for Y, 0.5 for U, 2 for Ni and Zn and 100 for Ti. The precision of replicate analysis is better than 5% for all analyzed trace elements except Zr and V, which have precisions of 5-8%. It is important to mention that although the recommendations of Verma and Santoyo (2005) and Verma *et al.* (2009) were not fully followed in

Table 1. Detrital modes from Upper Devonian sandstones of the Ilanqareh Formation. Qm monocrystalline quartz; Qm non Non-undulouse monocrystalline quartz; Qm un Undulouse monocrystalline quartz; Qpq polycrystalline quartz; Qp Polycrystalline quartzose; Qt Total quartzose grains; Q Total Qm and Qpq; F Total feldspar grains; L Unstable lithic fragments; Lt Total siliciclastic lithic fragments; Rf Total unstable rock fragments and chert.

Sample	Rock Type	Qpq	Qm	Qm un	Qm non	Qp	Qt	Q	F	Lt	L	Rf
27 IL	quartz arenite	3	216	78	138	3	219	219	4	3	0	0
30 IL	quartz arenite	5	227	82	145	10	237	232	3	12	2	7
32 IL	quartz arenite	3	228	89	139	5	233	231	4	5	0	2
33 IL	quartz arenite	4	206	79	127	7	213	210	5	9	2	5
34 IL	quartz arenite	4	233	91	142	7	240	237	3	7	0	3
35 IL	quartz arenite	2	220	85	135	2	222	222	2	3	1	1
37 IL	quartz arenite	3	234	93	141	3	237	237	8 *	3	0	0
55 IL	Sub arkose	5	231	83	148	7	238	236	9 *	9	2	4
56 IL	quartz arenite	1	218	87	131	3	221	219	3	3	0	2
57 IL	quartz arenite	5	216	82	134	5	221	221	4	5	0	0
60 IL	Sub arkose	5	216	88	128	10	226	221	6	11	1	6
61 IL	quartz arenite	7	231	92	139	10	241	238	5	11	1	4
62 IL	quartz arenite	9 *	224	82	142	9	233	233	3	9	0	0
64 IL	quartz arenite	10 *	226	83	143	12	238	236	7	12	0	2
65 IL	quartz arenite	8	245	91	154	11	256	253	2	11	0	3
66 IL	quartz arenite	10 *	229	89	140	13	242	239	4	13	0	3
67 IL	quartz arenite	9 *	253	98	155	12	265	262	3	12	0	3
68 IL	quartz arenite	7	235	89	146	9	244	242	5	10	1	3
69 IL	quartz arenite	9 *	238	90	148	11	249	247	4	13	2	4
70 IL	quartz arenite	5	230	90	140	8	238	235	3	8	0	3
71 IL	quartz arenite	5	235	91	144	8	243	240	5	9	1	4
72 IL	quartz arenite	7	256	101	155	7	263	263	4	7	0	0
73 IL	quartz arenite	9	223	87	136	14	237	232	7	14	0	5
74 IL	quartz arenite	4	237	99	138	6	243	241	6	6	0	2
75 IL	quartz arenite	5	237	96	141	8	245	242	3	10	2	5
76 IL	quartz arenite	7	237	95	142	10	247	244	3	10	0	3
98 IL	quartz arenite	4	243	101	142	6	249	247	6	8	2	4
29 IQ	quartz arenite	4	236	92	144	5	241	240	4	5	0	1
30 IQ	quartz arenite	2	230	91	139	4	234	232	3	6	2	4
32 IQ	quartz arenite	4	245	103	142	6	251	249	4	6	0	2
33 IQ	quartz arenite	2	243	99	144	3	246	245	2	4	1	2
34 IQ	quartz arenite	2	249	98	151	5	254	251	2	5	0	3
35 IQ	quartz arenite	4	241	93	148	5	246	245	4	5	0	1
37 IQ	quartz arenite	2	245	101	144	5	250	247	3	5	0	3
38 IQ	quartz arenite	4	247	99	148	7	254	251	3	7	0	3
39 IQ	quartz arenite	4	257	102	155	5	262	261	4	7	2	3
41 IQ	quartz arenite	3	228	89	139	5	233	231	4	6	1	3
43 IQ	quartz arenite	2	234	91	143	5	239	236	3	5	0	3
44 IQ	quartz arenite	5	256	105	151	7	263	261	3	7	0	2
45 IQ	quartz arenite	3	231	89	142	3	234	234	3	5	2	2
46 IQ	quartz arenite	4	238	96	142	4	242	242	4	4	0	0
47 IQ	quartz arenite	3	238	92	146	5	243	241	3	5	0	2
48 IQ	quartz arenite	3	249	98	151	5	254	252	5	5	0	2
49 IQ	quartz arenite	3	231	87	144	3	234	234	2	5	2	2
50 IQ	quartz arenite	2	236	91	145	2	238	238	4	2	0	0
51 IQ	quartz arenite	1	241	94	147	1	242	242	4	2	1	1
52 IQ	quartz arenite	3	241	103	138	3	244	244	3	4	1	1
53 IQ	quartz arenite	2	234	97	137	4	238	236	5	5	1	3
54 IQ	quartz arenite	4	226	88	138	5	231	230	4	7	2	3
56 IQ	quartz arenite	3	232	91	141	5	237	235	4	5	0	2
n		**45**	**50**	**50**	**50**	**50**	**50**	**50**	**47**	**50**	**50**	**50**
Mean		**3.9**	**235**	**92**	**143**	**6.4**	**241**	**239**	**3.8**	**7.0**	**0.6**	**2.5**
Stdev		**1.8**	**11**	**7**	**6**	**3.1**	**11**	**11**	**1.2**	**3.1**	**0.8**	**1.6**

* Unusual compositions were identified from single-outlier type discordancy tests (Verma, 1997; Verma *et al.*, 2008). Mean and standard deviation values were reported as rounded values after DODESYS application as suggested by Bevington and Robinson (2003) and Verma (2005).

this work, the DL data do show the systematic relationship put forth by these authors for quality control of chemical analysis, corresponding to several odd-even element pairs or sequences, such as Co-Ni (odd-even pair with the DL of 1 ppm (low) and 2 ppm (high), respectively) La-Ba (DL 0.3-10), Sc-Ti-V (DL 0.1-100-1), and Sr-Y-Zr-Nb (DL 1-0.4-1-0.1).

For the identification and elimination or separation of unusual compositions, the computer program DODESYS (by S.P. Verma and L. Díaz-González, manuscript in preparation) was used. This program uses highly precise and accurate critical values (Verma *et al.,* 2008; Verma and Quiroz-Ruiz, 2008) for the discordancy test method initially proposed by Verma (1997). The final statistical parameters (mean and standard deviation values) were reported after DODESYS application as rounded values (Bevington and Robinson, 2003; Verma, 2005).

RESULTS

Petrography and modal analysis

Texturally, the sandstones from Ilanqareh Formation are medium to fine-grained, with rounded to subrounded grains that are moderately to well-sorted. Note that the samples from the Ilanqareh section are finer than Ilanlu section. Many quartz grains at Ilanlu and Ilanqareh sections have incipient silica overgrowths and some samples especially at Ilanqareh section have carbonate cement, with minor amounts of clay mineral as cement. These silica overgrowths may be the result of pressure dissolution at the grain contacts, when the grains were buried under the pressure of the overlying rocks. Straight, concavo-convex and sutured grain contacts are present where framework grains have low cement content in sandstones from both sections.

The framework grains of sandstones at both localities are mainly quartz and less frequently of feldspar and rock fragments (Table 1).

Most of the quartz grains are monocrystalline, while a few percent of polycrystalline quartz are present in both sections especially at Ilanlu section (Figure 4a). Monocrystalline quartz grains exhibit unit extinction rather than undulose extinction (Figures 4a and 4b).

Compositionally, the most abundant lithic fragment is microcrystalline chert especially at Ilanlu section (Figure 4b). All studied thin sections in both stratigraphic sections contain small amounts of potassium feldspar (K) and plagioclase (Figure 4c). Although feldspars are rare in many samples from both sections, but when present, they are cloudy, which is related to alteration.

Some of the non-undulatory monocrystalline quartz contains inclusions of apatite and rutile needles, which show that that they may have been derived from plutonic source rocks or sedimentary recycling (Figure 4d). Accessory minerals in ascending order of decreasing are well-rounded zircon and apatite, as well as muscovite and biotite in both sections (Figures 4e and 4f).

The evidence of recycling (*e.g.*, rounded zircon) in the studied sandstone samples at both localities indicates that older sedimentary rocks may be considered as one of the major source rocks (*e.g.*, Hartley and Otava, 2001).

Modal analysis from point-counting of the framework grains are presented in Table 1. Monocrystalline quartz (Qm), polycrystalline quartz (Qp), total feldspar (F) and total lithic fragments (L) are identified. Varieties of monocrystalline quartz extinction types (undulose and non-undulose) are also recognized (Table 1).

Petrographic studies of samples show that, according to Folk (1980) classification, these sandstones are mainly quartz arenites (Figure 5), except two samples from Ilanlu section that they are classified as subarkose.

Trace elements geochemistry

Trace element concentrations of sandstones from Ilanqareh Formation at Ilanlu and Ilanqareh sections are reported in Tables 3 and 4. Likewise, average data of the upper continental crust composition (UCC) (Taylor and McLennan, 1985) are included as a reference.

Large-ion lithophile elements (LILE): Rb, Ba, Sr, Th, U

Compared with average upper continental crust (UCC) (Taylor and McLennan, 1985), analyzed sandstones at Ilanlu and Ilanqareh sections have relatively low concentrations in large ion lithophile elements (LILE), such as Rb, Th, U and distinct depletion especially in Sr and Ba (Figures 6a and 6b). The average abundances of Rb (21 ppm), Th (5.5 ppm), U (0.53 ppm), Sr (2 ppm) and Ba (50 ppm) from Ilanlu section and Rb (50.8 ppm), Th (9.7 ppm), U (1.3 ppm), Sr (98.9 ppm) and Ba (285.7 ppm) from Ilanqareh section are relatively low concentrations (Tables 3 and 4).

The general paucity of clay minerals in these sandstones from Ilanqareh Formation at Ilanlu and Ilanqarh sections probably influenced the depletions of these elements, such as Ba, Th and U, as they may be often hosted as cations in the phyllosilicate mineral structures (*e.g.*, Caracciolo *et al.,* 2009).

High field-strength elements (HFSE): Zr, Hf, Nb and Y

Zr, Nb, Hf and Y are preferentially partitioned into melts during crystallization and anatexis (Feng and Kerrich, 1990; Torres-Alvarado *et al.*, 2003), and as a result, these elements are enriched in felsic rather in mafic rocks. Additionally, they are thought to reflect provenance compositions as a consequence of their immobile behavior (Taylor and McLennan, 1985).

In general, the concentrations of some high field strength elements, such as Nb and Y, are lower in sandstones from Ilanlu section compared with those of the UCC (Figure 6a), but at Ilanqareh section are near the normalization value

Table 2. Recalculated modal point counts of the Upper Devonian sandstones of the Ilanqareh Formation. See Table 1 for details of the column heading abbreviations.

Sample	**Qt F L (%)**			**Qm F Lt (%)**			**Q F Rf(%)**			**Qm u Qm nu Qp(%)**		
	Qt	F	L	Qm	F	Lt	Q	F	Rf	Qp	Qm u	Qm nu
27 IL	98.2	1.8	0.0	96.9	1.8	1.3	98.2	1.8	0.0	1	36	63
30 IL	97.9	1.2	0.8	93.8	1.2	5.0	95.9	1.2	2.9	2	35	63
32 IL	98.3	1.7	0.0	96.2	1.7	2.1	97.5	1.7	0.8	1	39	60
33 IL	96.8	2.3	0.9	93.6	2.3	4.1	95.5	2.3	2.3	2	38	60
34 IL	98.8	1.2	0.0	95.9	1.2	2.9	97.5	1.2	1.2	2	38	60
35 IL	98.7	0.9	0.4	97.8	0.9	1.3	98.7	0.9	0.4	1	38	61
37 IL	96.7	3.3	0.0	95.5	3.3	1.2	96.7	3.3	0.0	1	39	59
55 IL	95.6	3.6	0.8	92.8	3.6	3.6	94.8	3.6	1.6	2	35	63
56 IL	98.7	1.3	0.0	97.3	1.3	1.3	97.8	1.3	0.9	0	40	60
57 IL	98.2	1.8	0.0	96.0	1.8	2.2	98.2	1.8	0.0	2	37	61
60 IL	97.0	2.6	0.4	92.7	2.6	4.7	94.8	2.6	2.6	2	40	58
61 IL	97.6	2.0	0.4	93.5	2.0	4.5	96.4	2.0	1.6	3	39	58
62 IL	98.7	1.3	0.0	94.9	1.3	3.8	98.7	1.3	0.0	4	35	61
64 IL	97.1	2.9	0.0	92.2	2.9	4.9	96.3	2.9	0.8	4	35	61
65 IL	99.2	0.8	0.0	95.0	0.8	4.3	98.1	0.8	1.2	3	36	61
66 IL	98.4	1.6	0.0	93.1	1.6	5.3	97.2	1.6	1.2	4	37	59
67 IL	98.9	1.1	0.0	94.4	1.1	4.5	97.8	1.1	1.1	3	37	59
68 IL	97.6	2.0	0.4	94.0	2.0	4.0	96.8	2.0	1.2	3	37	60
69 IL	97.6	1.6	0.8	93.3	1.6	5.1	96.9	1.6	1.6	4	36	60
70 IL	98.8	1.2	0.0	95.4	1.2	3.3	97.5	1.2	1.2	2	38	60
71 IL	97.6	2.0	0.4	94.4	2.0	3.6	96.4	2.0	1.6	2	38	60
72 IL	98.5	1.5	0.0	95.9	1.5	2.6	98.5	1.5	0.0	3	38	59
73 IL	97.1	2.9	0.0	91.4	2.9	5.7	95.1	2.9	2.0	4	38	59
74 IL	97.6	2.4	0.0	95.2	2.4	2.4	96.8	2.4	0.8	2	41	57
75 IL	98.0	1.2	0.8	94.8	1.2	4.0	96.8	1.2	2.0	2	40	58
76 IL	98.8	1.2	0.0	94.8	1.2	4.0	97.6	1.2	1.2	3	39	58
98 IL	96.9	2.3	0.8	94.6	2.3	3.1	96.1	2.3	1.6	2	41	57
29 IQ	98.4	1.6	0.0	96.3	1.6	2.0	98.0	1.6	0.4	2	38	60
30 IQ	97.9	1.3	0.8	96.2	1.3	2.5	97.1	1.3	1.7	1	39	60
32 IQ	98.4	1.6	0.0	96.1	1.6	2.4	97.6	1.6	0.8	2	41	57
33 IQ	98.8	0.8	0.4	97.6	0.8	1.6	98.4	0.8	0.8	1	40	59
34 IQ	99.2	0.8	0.0	97.3	0.8	2.0	98.0	0.8	1.2	1	39	60
35 IQ	98.4	1.6	0.0	96.4	1.6	2.0	98.0	1.6	0.4	2	38	60
37 IQ	98.8	1.2	0.0	96.8	1.2	2.0	97.6	1.2	1.2	1	41	58
38 IQ	98.8	1.2	0.0	96.1	1.2	2.7	97.7	1.2	1.2	2	39	59
39 IQ	97.8	1.5	0.7	95.9	1.5	2.6	97.4	1.5	1.1	2	39	59
41 IQ	97.9	1.7	0.4	95.8	1.7	2.5	97.1	1.7	1.3	1	39	60
43 IQ	98.8	1.2	0.0	96.7	1.2	2.1	97.5	1.2	1.2	1	39	61
44 IQ	98.9	1.1	0.0	96.2	1.1	2.6	98.1	1.1	0.8	2	40	58
45 IQ	97.9	1.3	0.8	96.7	1.3	2.1	97.9	1.3	0.8	1	38	61
46 IQ	98.4	1.6	0.0	96.7	1.6	1.6	98.4	1.6	0.0	2	40	59
47 IQ	98.8	1.2	0.0	96.7	1.2	2.0	98.0	1.2	0.8	1	38	61
48 IQ	98.1	1.9	0.0	96.1	1.9	1.9	97.3	1.9	0.8	1	39	60
49 IQ	98.3	0.8	0.8	97.1	0.8	2.1	98.3	0.8	0.8	1	37	62
50 IQ	98.3	1.7	0.0	97.5	1.7	0.8	98.3	1.7	0.0	1	38	61
51 IQ	98.0	1.6	0.4	97.6	1.6	0.8	98.0	1.6	0.4	0	39	61
52 IQ	98.4	1.2	0.4	97.2	1.2	1.6	98.4	1.2	0.4	1	42	57
53 IQ	97.5	2.0	0.4	95.9	2.0	2.0	96.7	2.0	1.2	1	41	58
54 IQ	97.5	1.7	0.8	95.4	1.7	3.0	97.0	1.7	1.3	2	38	60
56 IQ	98.3	1.7	0.0	96.3	1.7	2.1	97.5	1.7	0.8	1	39	60

Table 3. Whole rock trace element composition of representative Upper Devonian sandstones of the Ilanqareh Formation at Ilanlu section. Elemental concentrations are parts per million.

Sample no.	27 IL	30 IL	34 IL	35 IL	37 IL	60 IL	62 IL	69 IL	70 IL	72 IL	73 IL	74 IL	Mean	Sd. Dev	UCC
Ba	70	26	83	54	39	56	107	14	91	19	22	19	50	32	550
Rb	36.6	22.8	20	33.9	19.2	8.8	25.9	24.4	18.6	14	25	5.9	21	9	112
Zr	1136	234	909	862	819	183	468	273	743	885	226	426	600	330	190
Hf	16.6	8.38	11.6	14	18.9	10.5	8.79	12.5	19.1	13.78	11.9	8.23	12.9	3.8	5.8
Nb	7.3	1.67	4.7	9.72	4.17	1.16	5.24	1.01	6.42	6.9	2.2	2.2	4.4	2.8	12
Co	1.76	1.26	2.9	0.75	2.85	0.75	4.1	0.75	1.01	1.8	1.75	1.7	1.78	1	17
Cr	238	374	226	242	392	335	282	358	417	328	372	372.6	328	65	83
La	35.2	18.4	23.5	33.5	29.0	12.7	17.0	10.4	32.3	31.6	20.1	11.7	23	9	30
Y	14.8	4.4	11.3	6.9	8.8	7.4	7.06	3.6	7.3	7.5	3.3	3.9	7.2	3.4	22
Th	11.1	3.2	7.3	5.02	5.7	2.3	6.2	3.45	5.9	6.9	3.1	5.3	5.5	2.4	10.7
Sr	109	93.2	82	88.5	83.1	72	51.3	24.7	77.4	81.9	47.3	21.2	2	0.7	350
U	0.5	0.63	0.65	0.53	0.5	0.44	0.74	0.5	0.6	0.45	0.5	0.4	0.53	0.09	2.8
Sc	*4.75	1.23	2.73	2.42	1.98	0.9	2.73	1.06	2.61	2.57	1.85	1.42	2	0.7	13.6
Ni	6.6	43.5	11	10.5	50.3	3.4	12.4	4.34	41.7	66	59.8	167*	28	24	44
Pb	23.6	11.3	13.6	33.9	19.1	19	12.6	14.2	17.9	16.9	15	14.7	13.60	6.13	17
V	28.2	13.3	13.5	30.8	15.3	6.1	15.9	8.9	14.1	17.1	8.7	11.3	15	7	107
Zn	91	54	31.7	49.7	43.7	34.4	71.6	65.1	42.3	46	51	190	91	42.9	71
Ti	5198	681	4550	4466	3361	487	1983	459	1315	3277	845	1021	2303	1767	

No unusual compositions were identified from single-outlier type discordancy tests (Verma, 1997; Verma *et al.*, 2008). Mean and standard deviation values were reported as rounded values after DODESYS application as suggested by Bevington and Robinson (2003) and Verma (2005).

(Figure 6b). The average abundances of *HFSE* for Ilanlu section are: Zr (600 pm), Hf (12.9 ppm), Nb (4.4 ppm) and Y (7.2 ppm) and for Ilanqareh section are: Zr (239.3 ppm), Hf (9.5 ppm), Nb (9.1 ppm) and Y (17.9 ppm) (Tables 3 and 4).

Samples from the Ilanlu section are distinctly enriched in Zr (average 600 ppm), but samples from the Ilanlu section are slightly enriched in Zr (239 ppm) and both sections are distinctly enriched in Hf (average 12.9 ppm for Ilanlu and 9.5 ppm for Ilanqareh section) (Figure 6a and 6b). Zirconium is generally considered to be the least mobile elements during chemical weathering. Significant amounts of Zr are typically fixed in resistant minerals such as zircon.

Ferromagnesian trace elements: Co, Cr, Ni, Sc, V

Although the average abundances of Co (7.8 ppm), Sc (2 ppm), and V (15 ppm) from Ilanlu section and Co (3.3 ppm), Sc (7.3 ppm), and V (35.2 ppm) from Ilanqareh section are relatively low (Tables 3 and 4) in comparison to the average upper continental crust (UCC), Cr is distinctly enriched in both sections (average 328 ppm for Ilanlu and average 100 ppm for Ilanqareh section) and Ni is near the normalization value to relatively enriched in samples from Ilanlu section and is near the normalization value in Ilanqareh section (Figure 6a and 6b).

This enrichment in Cr and Ni may suggest some input of mafic and ultramafic materials from the source area as a minor source; however, the variations in Co, Cr and V values may also be due to changes in the oxidation state, therefore not reflecting source area composition. Thus, they must be used with caution (Bauluz *et al.*, 2000).

DISCUSSION

Provenance

Petrography

Because of the scarcity of feldspars and rock fragments in our studied samples, provenance was established mainly from the interpretation of quartz grain types. To evaluate the relative importance of quartz grain types for determining the provenance of the Upper Devonian sandstones from Ilanqareh Formation, we plotted polycrystalline (composite grains) quartz versus undulatory (strained) to non-undulatory (unstrained) monocrystalline quartz (Figure 7), following the technique of Tortosa *et al.* (1991). This plot suggests that quartz grains of the Ilanqareh sandstones at Ilanlu and Ilanqareh sections are of plutonic origin. The relatively high proportion of fine to medium-grain monocrystalline quartz in sandstones may be attributed to the disaggregation of original polycrystalline quartz during high energy and/or long distance transport from the source area (Dabbagh and Rogers, 1983).

The polycrystalline quartz grains are composed of five or more crystals with straight to slightly curved intercrystal boundaries (Figure 4a). This type suggests an origin from plutonic igneous rocks (Folk, 1980).

The petrographic characters are consistent with sandstones derived from an area of low relief on a stable shelf margin (*e.g.*, Amireh, 1991). Such characters may also indicate that the sandstones were derived from a cratonic interior (Burnett and Quirk, 2001) and were deposited on a passive margin (Emilia and Arribas, 2004).

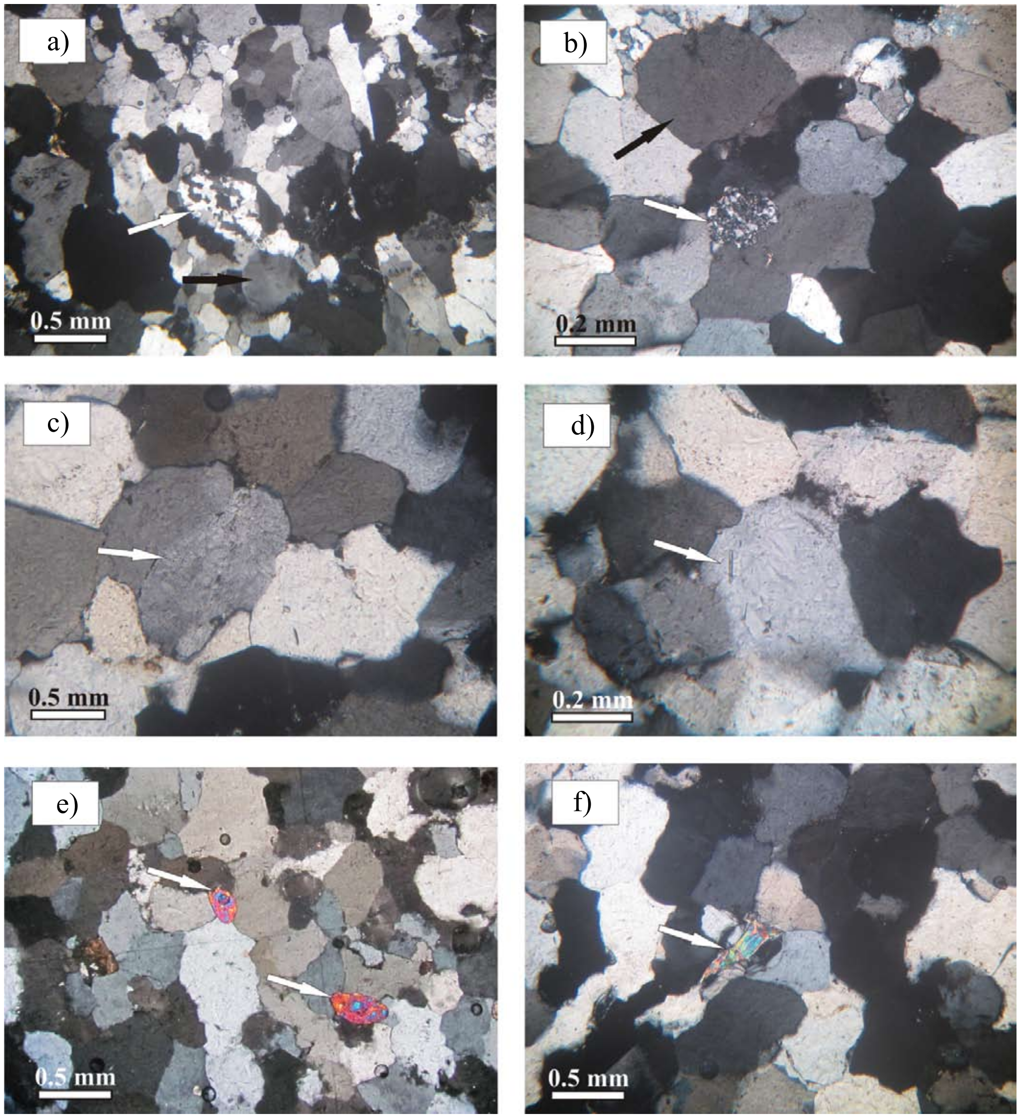

Figure 4. a) Photomicrograph showing quartz grains consisting mainly of monocrystalline quartz grains with undulose extinction (black arrow) and polycrystalline quartz grain (white arrow); b) Feldspar grain with a few alteration c) chert grain (white arrow) and monocrystalline quartz grains with nonundulose extinction (black arrow); d) quartz grain including inclusions of rutile needles; e) rounded grain of zircon as indicator of recycling (white arrows); and f) white arrow shows muscovite grain.

Geochemistry

In order to determine the source of sediments using trace-elements (for example, Th, Co, Ni, Sc, Zr, Hf and Nb), it is necessary to ascertain that the element is relatively immobile in the sedimentary cycle (Bhatia and Crook, 1986; McLennan, 2001; Shao *et al.*, 2001).

Th aboundances are higher in felsic than in mafic igneous source rocks and in their weathered products, whereas Co, Sc and Cr are more concentrated in mafic than felsic igneous rocks and in their weathered products. Mafic and felsic source rocks differ significantly in the ratios such of La/Sc, Th/Sc, La/Co, Th/Co and Cr/Th and hence provide useful information about the provenance of sedimentary rocks (*e.g.*, Cullers *et al.*, 1988; Cullers, 2000; Cullers and Podkovyrov, 2000). In this study, La/Sc, Th/Sc, La/Co and Th/Co values of the Upper Devonian sandstones are more similar to values for sediments derived from felsic source rocks than to those for mafic source rocks, thus suggesting felsic source rocks. However, Cr/Th is similar to values from mafic source rocks because of the enrichment of Cr (Table 5).

Floyd and Leveridge (1987) stated that the elemental ratio of La/Th plotted versus the concentration of hafnium demonstrates the degree of recycling in sandstones and it also provides information about the provenance. A La/Th versus Hf plot for the Upper Devonian sandstones at both sections shows an intense recycling and sedimentary source and a passive margin tectonic setting for these sandstones (Figure 8a).

Th/U in sedimentary rocks is of interest, as weathering and recycling typically result in loss of U, leading to an elevation in the Th/U ratio. The Th/U ratio in most up-

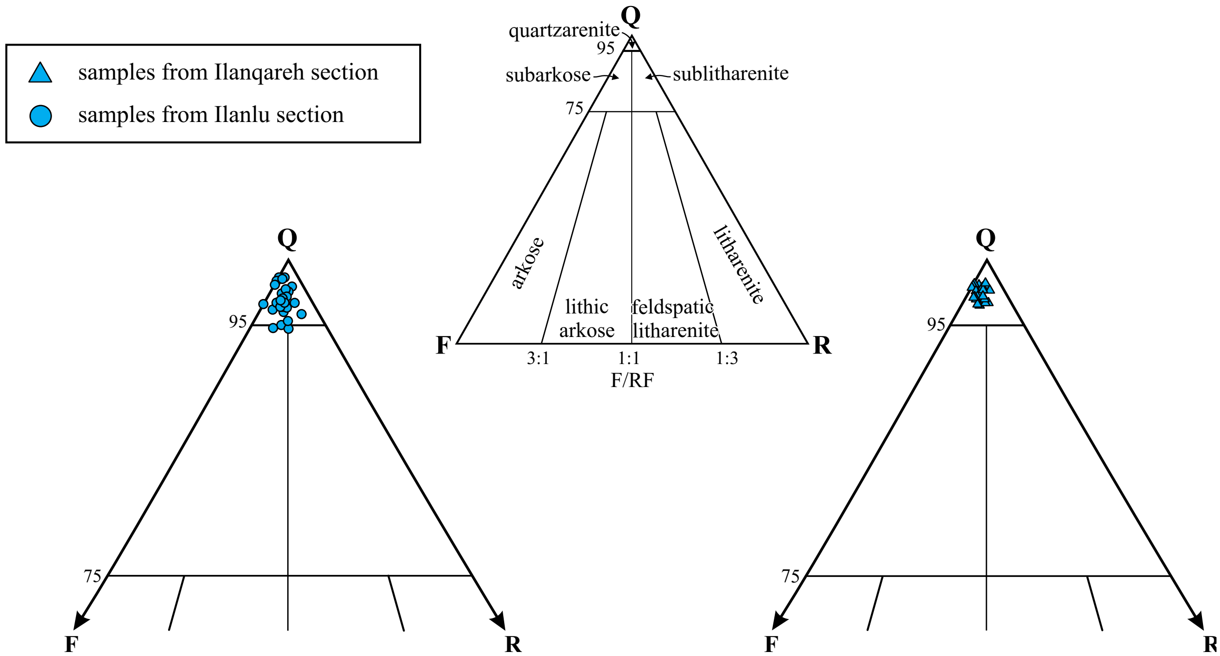

Figure 5. QFR triangular classification plot (Folk, 1980) of Sandstones from Ilanqareh Formation.

per crustal rocks is typically between 3.5 and 4 and Th/U values higher than 4 may indicate intense weathering in source areas or sediment recycling (McLennan *et al.,* 1993). Th/U ratios in the sandstones from Ilanqareh Formation at Ilanlu section range from 5.2 to 22 and for Ilanqareh section range from 3.7 to 11.8, indicating the derivation of these sandstones from recycling of the crust.

Th/Sc ratio commonly reflects the average composition of the source rocks. Scandium and Th are transferred quantitatively from source to sediment; hence, the ratio is used to deduce the composition of the source rock (McLennan *et al*., 1993). When Th/Sc is plotted on the diagram of Zr/Sc–Th/Sc (Figure 8b), the recycled source rocks for the all sandstone samples from the Ilanlu section and most samples from Ilanqareh section are further supported by their high Zr/Sc ratio. Strongly enriched Zr

Table 4. Whole rock trace element composition of representative Upper Devonian sandstones of the Ilanqareh Formation at Ilanqareh section. Elemental concentrations are parts per million (ppm).

Sample no.	**30 IQ**	**34 IQ**	**38 IQ**	**40 IQ**	**43 IQ**	**46 IQ**	**50 IQ**	**52 IQ**	**54 IQ**	**56 IQ**	**Mean**	**Sd. Dev**	**UCC**
Ba	380	206.2	223	282	352	395	221	252.5	319.8	224	285.7	71.1	550
Rb	54	43	63	91	36	33.4	48	42	52	46	50.8	16.6	112
Zr	256	224	229	269	235	221	241	260	215	243	239.3	17.9	190
Hf	8.7	9.2	10.4	9.4	8. 2	8.3	11.1	10.1	9.1	8.5	9.5	0.9	5.8
Nb	9.2	8.5	10.7	9.3	7.6	6.6	11.2	6.8	6.9	14.1	9.1	2.4	12
Co	4.8	3.9	5.1	2.9	3.2	3.8	2.9	1.8	1.8	2.5	3.3	1.1	17
Cr	170.5	95	114	104	163	53	61	86	77	83	100.7	39.3	83
La	41	35	37.6	43.2	24	29	20.64	19.99	18.23	30.13	29.9	9.1	30
Y	21	19.2	24.3	23.2	18.2	13.1	10.3	14.3	16	19.68	17.9	4.5	22
Th	10.8	8.7	10.3	10.6	9.2	9.12	9.8	9	10.4	8.6	9.7	0.8	10.7
Sr	92	81	108	109	121	96	104.5	102	79.9	95.4	98.9	12.8	350
U	1.5	1.02	1.38	0.9	0.84	1.56	0.84	0.9	1.33	2.3	1.3	0.5	2.8
Sc	7	5.2	9	10	5.1	6	6	5.4	6	13	7.3	2.6	13.6
Ni	21	26	31	43.5	35	51	28	21	23	18	29.8	10.7	44
Pb	13.5	10.8	10.7	10.2	8.5	9.3	8.9	9.5	10.7	9.7	10.2	1.4	17
V	43	38	29	24	52	60	23	32	28	23	35.2	12.9	107
Zn	33	42	55	61	29.8	25	34	28	44.1	28.8	38.1	12.2	71
Ti	1235	842	1696	1510	753	1907	2246	819	2515	2501	1602.4	684.2	

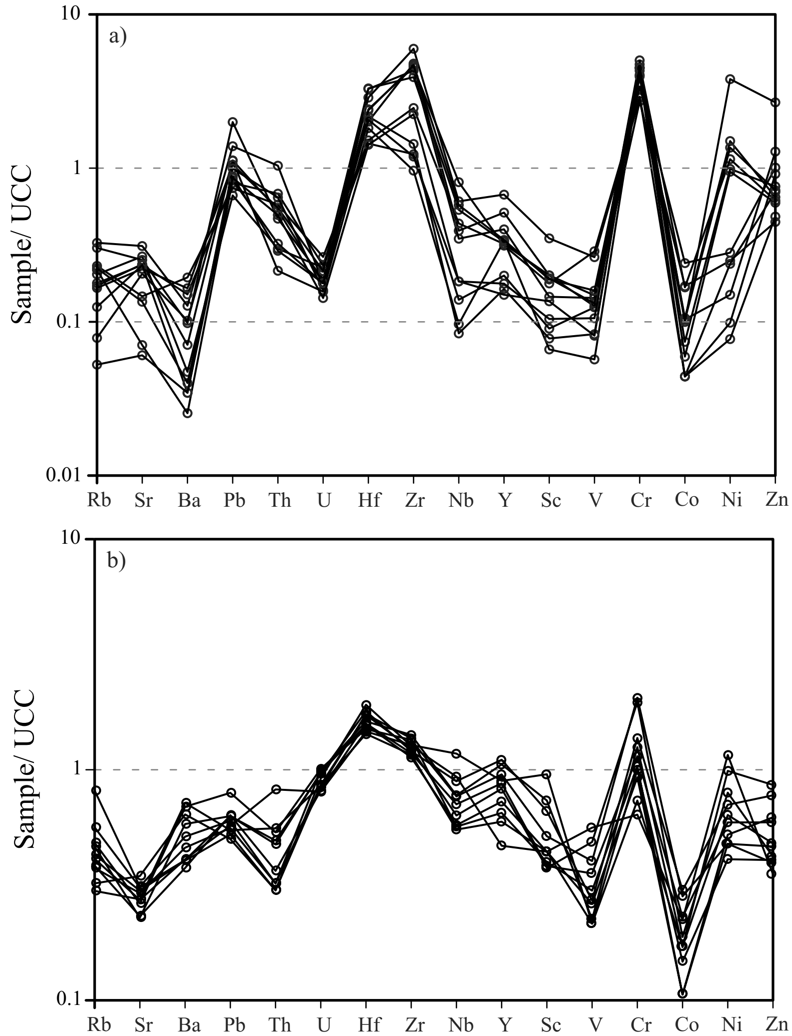

Figure 6. Multi-element normalized diagrams for sandstones of Ilanqareh Formation normalized against average upper continental crust (Taylor and McLennan, 1985).

in zircon can be easily recycled and Sc is present in labile phases. Therefore, the Zr/Sc ratio is considered as one of the proxy to evaluate the presence or absence of recycling (McLennan *et al.*, 1993). But three samples from Ilanqareh section fallow the trend of first order sediments and show a simple positive correlation between these ratios.

Tectonic setting

Petrography

Sandstones from different tectonic settings have different detrital components and geochemical composition (Dickinson *et al.*, 1983; Bhatia, 1983; Kroonenberg, 1994; Critelli and Nilsen, 2000; Roser *et al.*, 2002; Yan *et al.*, 2006). In the following sections, we will discuss how the detrital and chemical compositions of the Upper Devonian Sandstones may be used to determine their tectonic setting.

Plate tectonic processes control the characteristics of the detrital grains of sandstones (Dickinson *et al.*, 1983; Marsaglia, 2004). Plotting data from the modal analysis of the Ilanqareh Sandstones in the ternary Qt-F-L and Qm-F-Lt diagrams of Dickinson *et al.* (1983) shows that the Upper Devonian sandstones at both localities falls entirely in the cratonic interior and close to the recycled orogen field (Figure 9).

As pointed out by Dickinson *et al.* (1983), sandstones plotting in the cratonic field are mature sandstones derived from relatively low-lying granitoid and gneissic sources, supplemented by recycled sands from associated platform or passive margin basins. However, process of diagenesis may change the original composition of the rocks, which in turn affect the results of Q-F-L plot (McBride, 1985). Hence, such provenance determination has to be considered with caution.

Geochemistry

Trace elements are generally thought to be quantitatively transported into clastic sedimentary rocks after

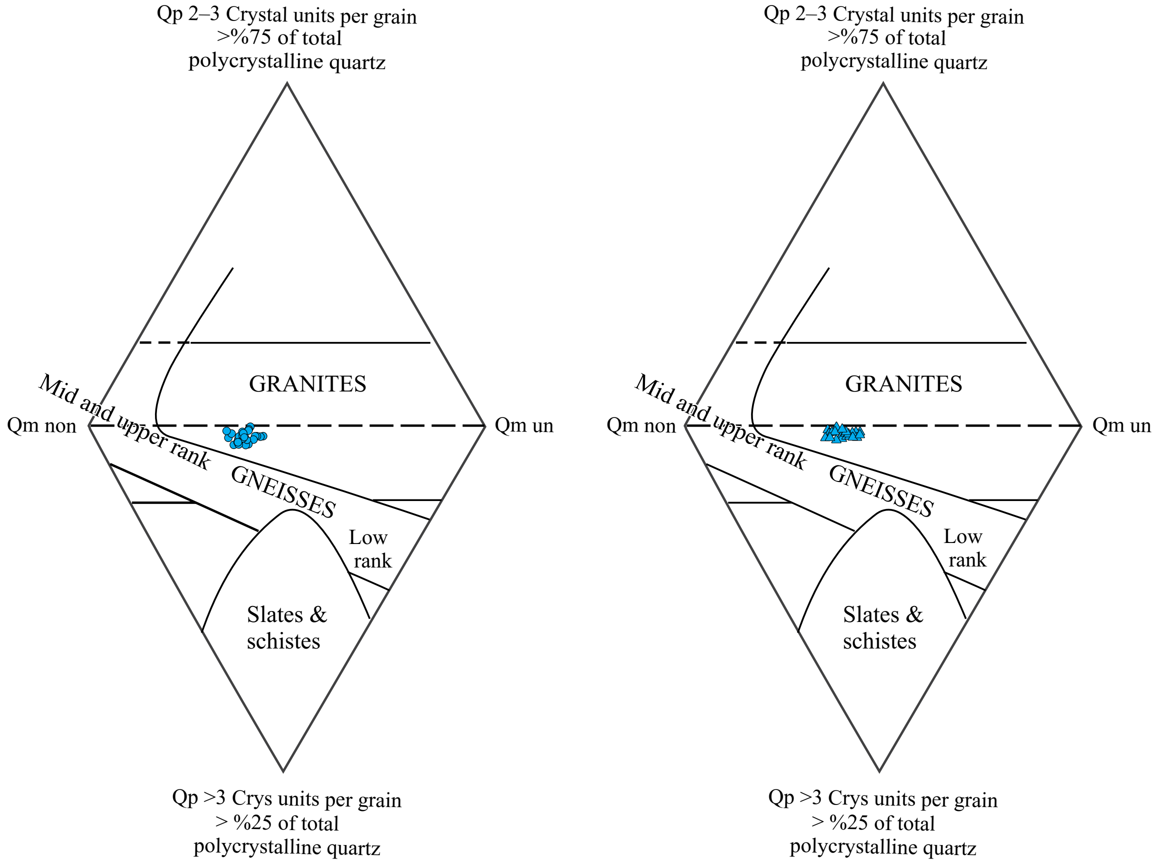

Figure 7. Varietal quartz diamond plot currently used to discriminate sands sourced by different types of crystalline rocks, on the basis of the extinction pattern and polycrystallinity of quartz grains. Qmnon: low-undulosity monocrystalline quartz grains; Qmun = high-undulosity monocrystalline quartz grains; Qp2–3 = coarse-grained polycrystalline quartz grains; Qp > 3 = fi ne-grained polycrystalline quartz grains. Upper Devonian sandstones are compared with granites provenance fields after Tortosa *et al.* (1991). Symbols as Figure 5.

weathering, and thus, they may reflect the signature of parent materials and these elements can be used in sedimentary rocks to determine their provenance and tectonic setting (*e.g.*, McLennan *et al.*, 1993; Bahlburg, 1998; Burnett and Quirk, 2001; Zimmermann and Bahlburg, 2003; Cingolani *et al.*, 2003; Li *et al.*, 2005).

The strongly negative Sr-anomaly, which is suggesting the older recycled environments/passive margin setting, is common in all of the sandstone samples at Ilanlu and Ilanqareh sections (Figure 6). Small positive Hf-Zr anomalies at both sections suggest a slight influence of mature sedimentary detritus (zircon, rutile) of a passive continental margin (*e.g.*, Mader and Neubauer, 2004). Furthermore, we used the triangle diagrams (La–Th–Sc and Th–Sc–Zr/10 and Th–Co–Zr/10) and discrimination diagram of La/Sc versus Ti/Zr (Bhatia and Crook, 1986), to understand the tectonic setting of studied samples based on these plots. Most of the Ilanqareh sandstones at both sections cluster within or close to the passive continental margin field (Figure 10); therefore, they may have been

Table 5. Range of elemental ratios from Upper Devonian sandstones of the Ilanqareh Formation at Ilanlu and Ilanqareh sections compared to elemental ratios in sedimens derived from felsic rocks, mafic rocks and in the Upper Continental Crust.

Elemental ratio	**Upper continental crust[2]**	**Range of sediment from mafic sources[1]**	**Range of sediment from felsic sources[1]**	**Range of sandstones from Ilanqareh section *n* = 10**	**Range of sandstones from Ilanlu section *n* = 12**
La/Sc	2.21	0.43 – 0.86	2.50 – 16.3	2.3 – 6.7	6.2 - 15
Th/Sc	0.79	0.05 – 0.22	0.84 – 20.5	0.7 – 1.8	1.7 – 3.7
La/Co	1.76	0.14 – 0.38	1.80 – 13.8	7.1 – 14.9	4.1 – 44.7
Th/Co	0.63	0.04 – 1.40	0.67 – 19.4	2 – 5.8	1.5 – 6.7
Cr/Th	7.76	25 – 500	4.00 – 15.0	5.8 – 17.7	21.4 – 145.7

[1] Cullers (2000); Cullers and Podkovyrov (2000); Cullers *et al.* (1988). [2] McLennan (2001); Taylor and McLennan (1985).

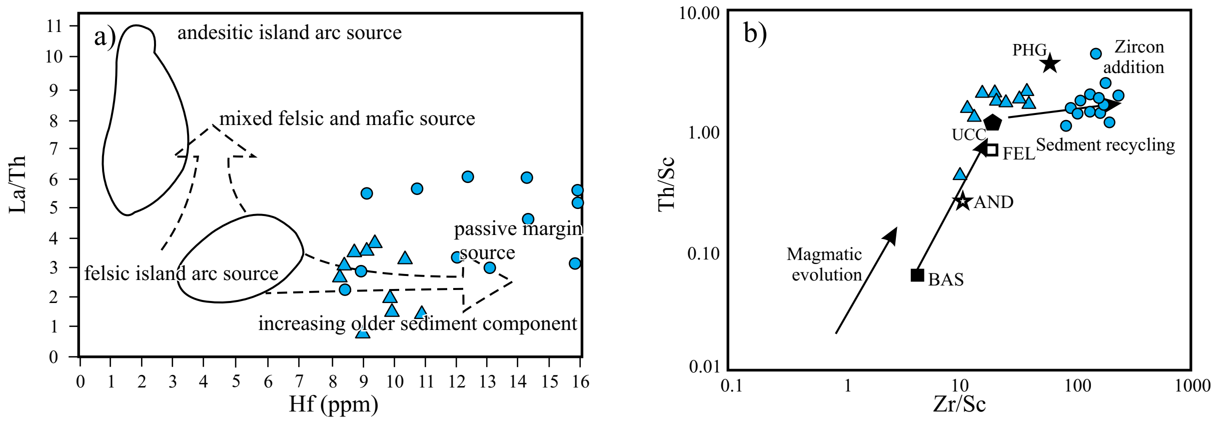

Figura 8. a) Source rock Hf–La/Th— discrimination diagram for the discussion of the clastic sediments and their compositions (Floyd and Leveridge, 1987) for Upper Devonian sandstones from Ilanqareh Formation at Ilanlu and Ilanqareh sections. Symbols as Figure 5. b) Plot of Th/Sc versus Zr/Sc of Upper Devonian sandstones from Ilanqareh Formation (modified after McLennan *et al.*, 1993). The Upper Devonian sandstones are enriched in zircon, due to sedimentary sorting and recycling. Legend: PHG= Phanerozoic granite; FEL= felsic volcanic rock; AND= andesite; BAS= basalt (igneous rock averages from Condie, 1993); UCC= Upper Continental Crust (composition after Taylor and McLennan, 1985). The lower and intermediate arrows (compositional trend) define the trend expected in first-cycle sediments due to magmatic evolution from mafic to felsic; upper arrow shows the trend produced by the addition of zircon during sedimentary sorting and recycling. Symbols as Figure 5.

derived from such tectonic setting, although some samples plot in continental island arc. This interpretation must be made cautiously, because specific tectonic settings do not necessarily produce rocks with unique geochemical signatures (Bahlburg, 1998).

Probebale source rocks (regional perspective)

A paleogeographic map of the Late Ordovician to Late Devonian of northern Arabia suggests that North Africa and Arabia formed a broad stable continental shelf on the northern margin of the Gondwana supercontinent (Beydoun, 1991; Al-Juboury and AL-Hadidy, 2009) bordering the Paleo-Tethys Ocean (Figure 11).

Studies of the Late Ordovician to Late Devonian rocks in the north of Arabian plate show that they were deposited in either terrestrial or shallow marine environments (Al-Harbi and Khan, 2008) (Figure11).

Typical shallow-marine deposits are recorded in southern Turkey (Cater and Tunbridge, 1992), northern Syria (Best *et al.*, 1993), northwest Iran (Stocklin *et al.*, 1964) and northern Iraq (Wolfard, 1981). Shallow-marine deposits show that these areas have been located the southern marginal shelf of the Late Ordovician to Late Devonian Paleo-Tethys Ocean. In addition, most of these studies show that the siliciclastic deposits prograded from south (where the Arabo-Nubian Shield crops out at the present time) to north, towards the northern borders of North Africa and Arabia (Figure11). For example, Devonian Jauf sandstones (of passive margin tectonic setting) of Saudi Arabia are also reported to be deposited on a low-lying land mass forming the stable continental margin of the Arabian-Nubian Shield, flanking the southern margin of the Paleo-Tethys Ocean (Al-Ramadan *et al.,* 2004).

As stated above, Stump *et al.* (1995) indicated that the Late Devonian to Early Carboniferous sediments are not uniformly distributed across the Arabian Peninsula due to uplift and erosion associated with the Hercynian Orogeny during the end of Devonian to Carboniferous. This tectonic event is interpreted to be the crustal response to regional compression caused by the initiation of subduction of Paleo-Tethyan oceanic crust near the margin of Gondwana along Turkey and Iran (McGillivery and Husseini, 1992).

Considering paleogeographic data during the Late Devonian and petrographic and geochemical studies, the source of sandstones for the Ilanqareh Formation might be assigned to Arabian shield, but the effect of recycling due to Hercynian tectonic event on these sandstones might be considered. Such provenance interpretation has to be considered with caution because the role of sedimentary environment and diagenesis.

CONCLUSIONS

The provenance of the Upper Devonian sandstones of Ilanqareh Formation at Ilanlu and Ilanqareh sections in northwestern Iran has been assessed using integrated petrographic and geochemical (trace-elements) studies. The results are generally in agreement. Petrographically, most of these sandstones are Quartz arenites except two samples from Ilanlu section. The petrographic (framework mineralogy and quartz types) and geochemical characteristics suggest plutonic igneous rocks as major parent rocks for them and are affected by recycling. Recycling sources for these sandstones can be related to the Hercynian orogeny in NW Iran.

This approach has revealed that the sandstones of Ilanqareh Formation were primarily derived from

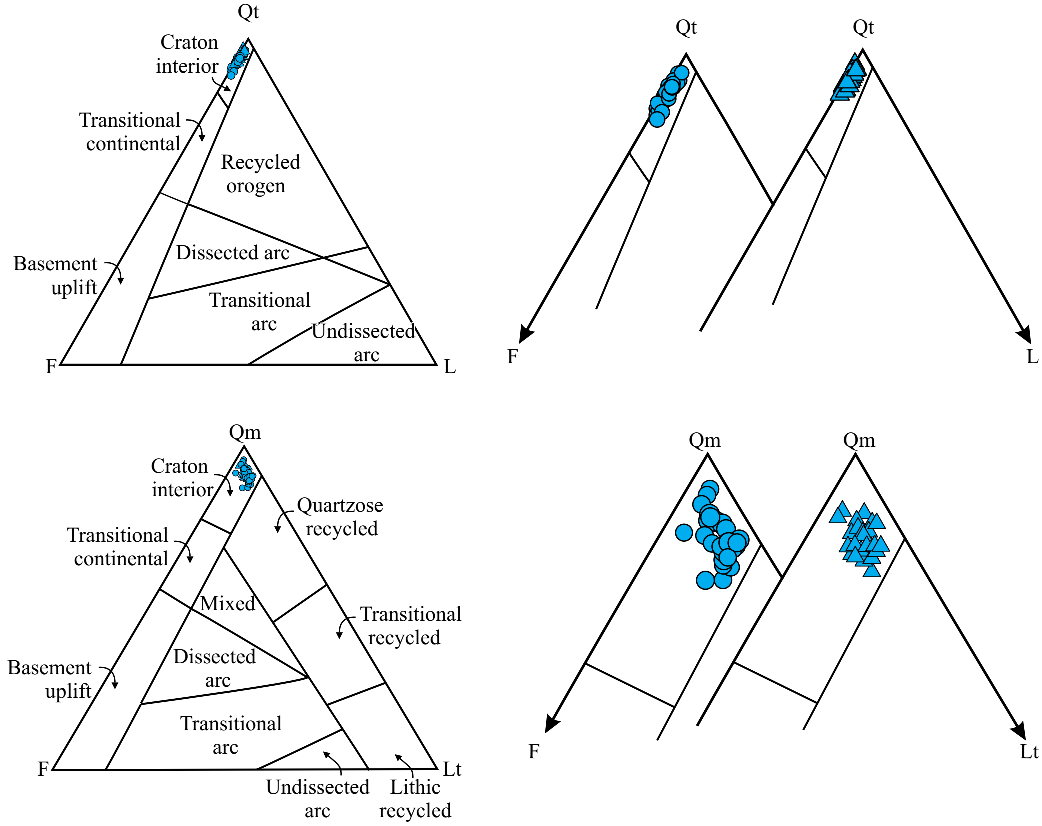

Figure 9. QtFL and QmFLt ternary diagrams for the Upper Devonian sandstones from Ilanqareh Formation based on Dickinson *et al.* (1983). Symbols as Figure 5.

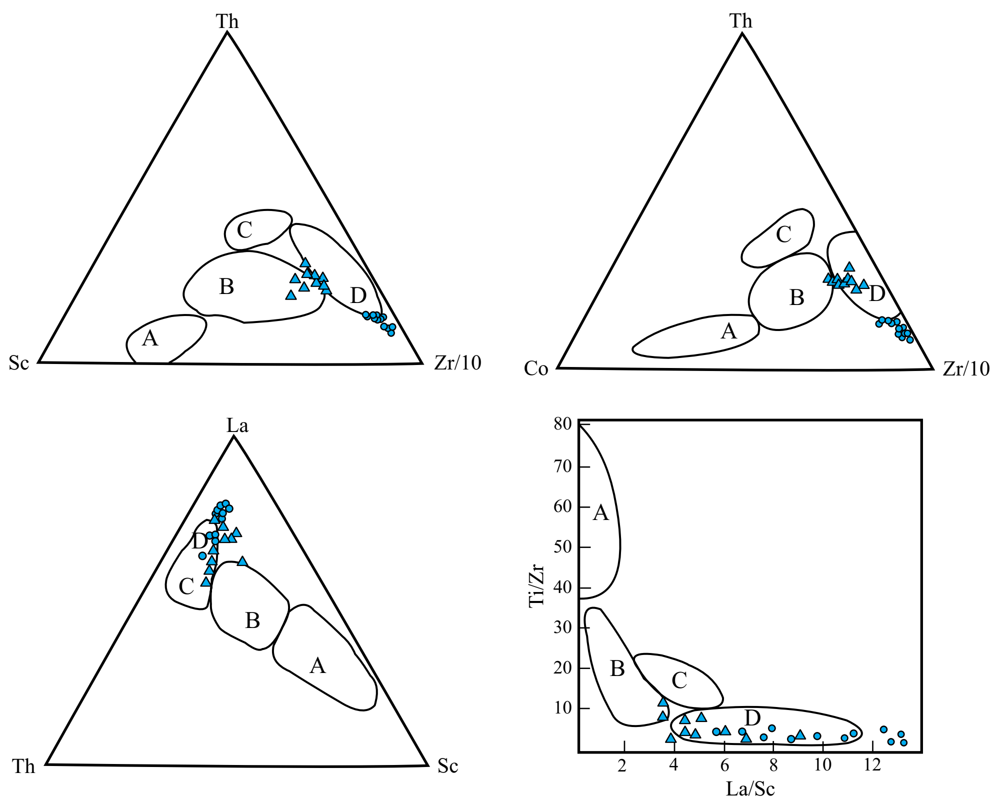

Figure 10. Trace element composition of the sandstones from Ilanqareh Formation on the triangle and bivariate tectonic setting discrimination diagrams of Bhatia and Crook (1986). .See text for details. Legend: A=oceanic island arc; B=continental island arc; C=active continental margin; D=passive continental margin. Symbols as Figure 5.

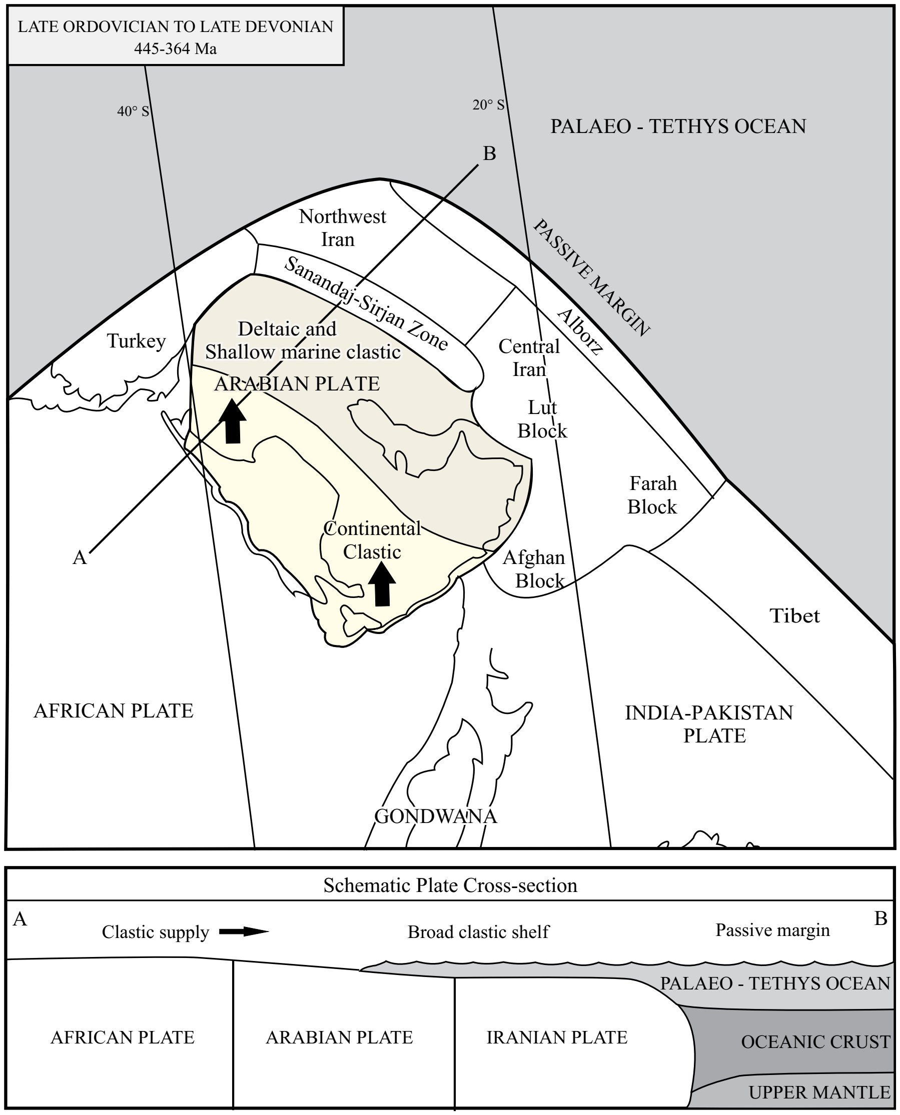

Figure 11. Paleo-tectonic map of Late Ordovician to Late Devonian time of the Arabian Plate and adjacent blocks. (Al-Juboury and Al-Hadidy, 2009).

sources typical of a cratonic interior. Also, the provenance characteristics based on petrographic and geochemical methods suggest that the Ilanqareh sandstones were deposited on a passive margin that received large amounts of mature detritus from the source areas. Moreover, the data are consistent with a long distance transport, possibly over the Arabian shield that might have supplied sands to the depositional basin along the passive marginal coast of the Paleo-Tethys.

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