Revista Mexicana de Ciencias Geológicas, v. 25, núm. 2, 2008, p. 247-260

Petrography and geochemistry of Ahwaz Sandstone Member of Asmari Formation, Zagros, Iran: implications on provenance and tectonic setting

Mahdi Jafarzadeh and Mahboobeh Hosseini-Barzi*

Faculty of Earth Science, Geology Department, Shahid Beheshti University, Iran.
** hosseini@khayam.ut.ac.ir*

ABSTRACT

An integrated petrographic and geochemical study of the Ahwaz Sandstone Member of Oligocene-Miocene age, Asmari Formation in Zagros, southwest Iran, was carried out to infer their provenance and tectonic setting. This study is based on the analysis of core samples from three subsurface sections (wells Az-85, Az-11, and Az-89) in Ahwaz oil field in the Dezful embayment subzone.

On the basis of the framework composition (point counting) and whole-rock geochemistry (major elements), the sandstones are classified as quartzarenite, sublitharenite, and subarkose types. Petrographic studies reveal that these sandstones contain quartz, feldspars and fragments of sedimentary and metasedimentary rocks. The modal analysis data of 50 collected (medium size and well sorted) samples, imply a recycled orogen and craton interior tectonic provenance. Moreover, petrographic point count data indicate quartz-rich sedimentary (recycled), middle to high-grade metamorphic, and plutonic parent rocks for the Ahwaz Sandstone. Tectonic setting discrimination diagrams based on major elements suggest a quartzose sedimentary provenance in a passive continental margin. As indicated by the CIW´ index (chemical index of weathering) of the Ahwaz Sandstone (average value of 67) their source area underwent "intense" recycling but "moderate" degree of chemical weathering. The petrography and geochemistry results are consistent with a semiarid climate and low-relief highlands.

Key words: provenance, tectonic setting, sandstone, geochemistry, Ahwaz Sandstone Member, Asmari Formation, Iran.

RESUMEN

Un estudio petrográfico y geoquímico del Miembro de Arenisca Ahwaz del Oligoceno-Mioceno, Formación Asmari en Zagros, suroeste de Iran, fue realizado con el objeto de inferir su proveniencia y el ambiente tectónico. Este estudio se basó en el análisis de muestras de núcleos de tres secciones (pozos Az-85, Az-11, and Az-89) del campo petrolero Ahwaz, en la subzona de la bahía de Dezful.

Usando la abundancia de los minerales principales (conteo de puntos) y la geoquímica de roca total (elementos mayores), las areniscas se clasificaron como cuarzoarenita, sublitoarenita y subarcosas. El estudio petrográfico revela que estas areniscas consisten de cuarzo, feldespatos y fragmentos de rocas sedimentarias y metasedimentarias. El análisis modal de 50 muestras recolectadas de grano medio y bien clasificadas, indica la proveniencia tectónica de un orógeno reciclado y del interior del cratón. Además, los datos petrográficos del conteo de puntos señalan que las rocas parentales fueron rocas sedimentarias ricas en cuarzo (recicladas), metamórficas de grado medio a alto, así como plutónicas. Los diagramas para ambientes tectónicos basados en elementos mayores sugieren una proveniencia sedimentaria rica en cuarzo en un ambiente tectónico de margen pasivo continental. Como lo indica el índice CIW´ (índice *químico de intemperismo) para las muestras de la Arenisca Ahwaz (con valor promedio de 67) su área fuente fue sujeta a reciclaje intenso, pero a intemperismo químico de grado moderado. Los resultados de la petrografía y la geoquímica son consistentes con un clima semiárido y con terrenos poco elevados (de bajo relieve).*

Palabras clave: proveniencia, ambiente tectónico, arenisca, geoquímica, Miembro de Arenisca Ahwaz, Formación Asmari, Irán.

INTRODUCTION

The combination of petrography and geochemistry data of sedimentary rocks can reveal the nature of source regions, the tectonic setting of sedimentary basins, and paleoclimate conditions (*e.g.*, Dickinson and Suczek, 1979; Valloni and Mezzardi, 1984; Bhatia and Crook, 1986; McLennan *et al.*, 1993; Armstrong-Altrin *et al.*, 2004). Basu *et al.* (1975) and Tortosa *et al.* (1991) used the frequency of different types of quartz grains to infer the type of source rocks. Thus, simple petrographic descriptions of different quartz constituents can be utilized for this purpose (Folk, 1974; Blatt *et al.*, 1980; Asiedu *et al.*, 2000). The determination of the tectonic setting of sandstones using the framework mineral composition (detrital modes) was first proposed by Crook (1974) and has since undergone considerable refinement (*e.g.*, Dickinson and Suczek, 1979; Dickinson *et al.*, 1983, Weltje, 2002, Basu, 2003). The main assumption behind sandstone provenance studies is that different tectonic settings contain their own rock types, which when eroded, produce sandstones with specific compositional ranges (*e.g.*, Dickinson and Suczek, 1979; Dickinson *et al.*, 1983; Dickinson, 1985).

Although some geochemical ratios can be altered during weathering (through oxidation) (Taylor and McLennan, 1985) and/or diagenesis (Nesbitt and Young, 1989; Milodowski and Zalasiewicz, 1991), as long as the bulk composition of a rock is not totally altered, geochemical analysis is a valuable tool in the study of sandstones (McLennan *et al.*, 1993). Major element discrimination diagrams (*e.g.*, Bhatia, 1983) have been used to discriminate the tectonic settings of sedimentary basins and have been commonly applied in more recent publications (*e.g.*, Kroonenberg, 1994; Zimmermann and Bahlburg, 2003; Armstrong-Altrin *et al.*, 2004), although,caution is required in their indiscriminate use (Armstrong-Altrin and Verma, 2005). The most important clues for the tectonic setting of the basin comes from the relative depletion of oxides like CaO and Na_2O (the most mobile elements) and enrichment of SiO_2 and TiO_2 (the most immobile elements), among others. These oxides are assumed to show enrichment or depletion in quartz, K-feldspar, micas, and plagioclase. The ratio of the most immobile elements to the most mobile ones increases toward passive margins due to the relative tectonic stability (Bhatia 1983; Kroonenberg 1994; Roser and Korsch 1986; Zimmermann and Bahlburg, 2003; Armstrong-Altrin *et al.*, 2004) and hence prolonged weathering. This can be recorded in sediments as paleoclimate index (Nesbitt and Young, 1982; Harnois, 1988; Chittleborough, 1991) and high degree of sediment recycling.

The carbonate rocks of the Asmari Formation (the major oil reservoir in the Zagros mountain) are well studied (Lacassagne, 1963; Seyrafian, 2000; Vaziri-Moghaddam *et al.*, 2006). However, only a few petrography and palaeoenvironment studies of Ahwaz Sandstone Member of this formation (*e.g.*, Zahedinezhad, 1987; Buck, 1991) have been reported. In this study, we present new petrography, point count and geochemical data from three subsurface sections (from three wells: Az-85, Az-11 and Az-89) of the Ahwaz Sandstone Member in the Dezful embayment zone, southwest of Zagros structural province (Figure 1). These data were utilized for reconstructing the parent rock assemblages of these sandstones, their tectonic provenance, and the physiographic conditions under which these sediments deposited. Although these kinds of results from Asmari reservoir are of considerable importance for oil industries, the consistency of different approaches (petrography, point counting and geochemistry) in provenance and tectonic setting studies of sandstones like Ahwaz Sandstone is of further significance, being the main reason why we carried out such an integrated study.

GENERAL GEOLOGY OF THE STUDY AREA

The geological evidence suggests that the Zagros region was part of a passive continental margin, which subsequently underwent rifting during the Permo-Triassic and collision during the Late Tertiary (Stocklin, 1974; Berberian and King, 1981; Beydoun *et al.*, 1992). In fact, the Zagros fold–thrust belt lies on the northeastern margin of the Arabian plate and has been divided into NW–SE trending structural zones (imbricated and simply folded belt) parallel to the plate margin separated by major fault zones such as the High Zagros and Mountain Front Faults (Figure 1). In addition to the tectonic divisions parallel to the mountain belt, the belt has also been divided laterally to the Lurestan, Dezful embayment and Fars regions from northwest to southeast.

The Asmari Formation (one of the best-known carbonate reservoirs in the world) was deposited in the Oligocene-Miocene shallow marine environment of the Zagros foreland basin (Alavi, 2004) and it is best developed in the Dezful embayment zone. Lithologically, the Asmari Formation consists of 314 m of limestones, dolomitic limestones, and argillaceous limestones (Motiei, 1993). In the south of Dezful embayment, its lithology changes into a mixed siliciclastic-carbonate deposit consisting of carbonate beds with several intervals of sandstone, sandy limestone and shale. This facies provides the Ahwaz Sandstone Member in some oil fields such as Ahwaz, Marun and Mansuri (Motiei, 1993).

The Ahwaz Sandstone is a shoreface deposit. Their distribution along the strike of the Zagros foreland basin is restricted to the southwestern margin as a number of elongate northwest–southeast siliciclastic bars (Alavi, 2004). Alsharhan and Nairn (1997) considered the Ahwaz Sandstone to correlate with Ghar Formation in Kuwait whose clastic input is believed to have been derived from the pre-rift uplift of the Red Sea to the west (Alsharhan and Nairn, 1997). The localization of the Ghar/Ahwaz delta of southern Iraq and southwestern Iran was probably influenced by deep-seated 'Hercynian'-age (~330 Ma) lineaments that extended northward from the Central Arabian Arch (Ziegler, 2001).

SAMPLING AND METHODS

Nine hundred samples were collected from three wells in the Ahwaz oil field (well no. Az-85A, Az-89 and Az-11; 300 samples from each well) to represent the entire thickness of the Asmari Formation and thin sections were prepared, which were etched and stained for calcite and dolomite as matrix. Following a detailed petrographic study of thin sections, 50 thin sections of the Ahwaz Sandstone were selected for modal analysis, among 450 sandstone samples, from the three subsurface sections (12 samples from well Az-85A, 13 samples from well Az-89 and 25 samples from well Az-11) (Figure 2). The sample selection was based on petrography to choose well-sorted and unweathered, fine- to medium-grained, sand-size samples and to cover the entire thickness of the formation. Framework mineral composition (modal analysis) was quantified using the point-counting method of Gazzi-Dickinson as described by Ingersoll *et al.* (1984).

In the Gazzi-Dickinson method (Ingersoll *et al.*, 1984), minerals > 0.625 mm within lithoclasts are counted acording to the mineral type (phaneritic grains: crystal size exceeding 0.0625 mm; aphanitic grains: crystal size less than 0.0625 mm). Classification of grain types was done

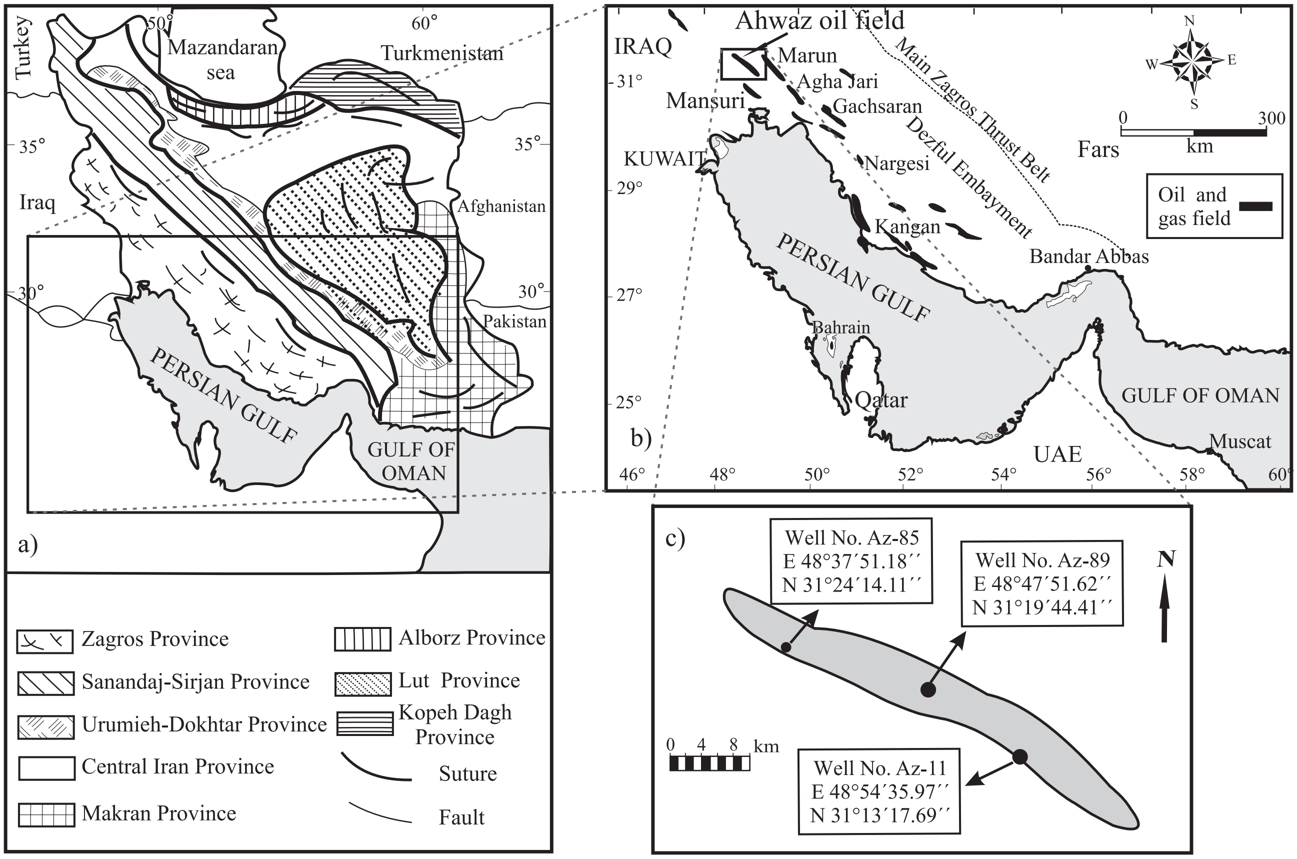


Figure 1. a: General map of Iran showing all the eight geologic provinces. The study area is located in the Zagros province (modified after Vaziri-Moghaddam *et al.*, 2006); b: location of Ahwaz oil field in the Dezful Embayment of Zagros basin (modified after Insalaco *et al.*, 2006); c: location of the studied wells within the Ahwaz oil field.

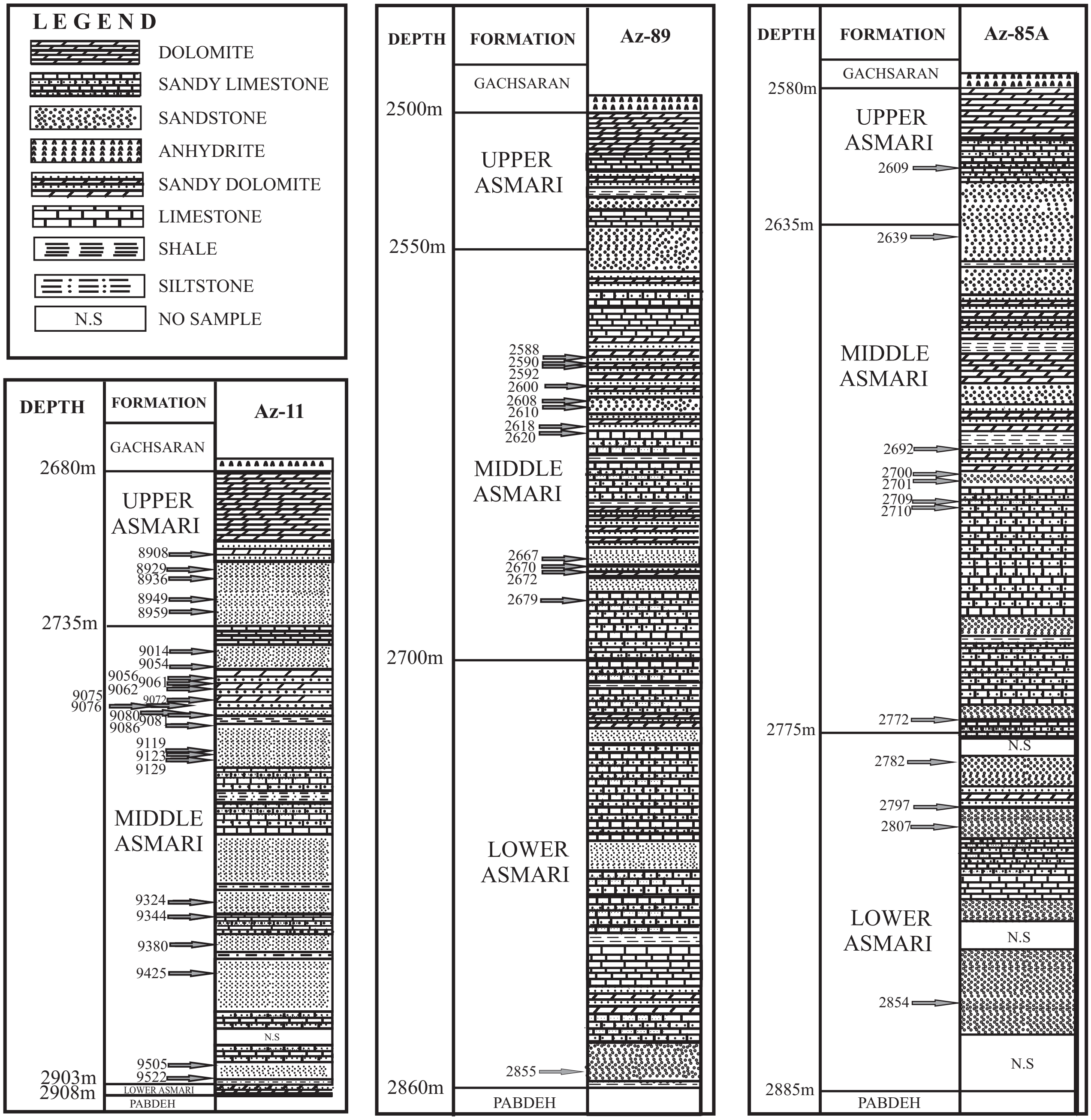


Figure 2. Columnar sections of the Asmari Formation in three subsurface sections of the Ahwaz oil field, showing the location (arrows) of sandstone and calcareous sandstone samples for point count analysis.

following the Dickinson (1985) method (Table 1). The grid spacing used in point counting exceeded the grain size so as to avoid individual grains being counted more than once (*e.g.*, Van Der Plas and Tobi, 1965). In order to reconstruct the original detrital composition of the sandstone, the effects of diagenesis such as calcitization, zeolitization, and albitization of feldspars (Shanmugam, 1985) were taken into consideration as much as possible during counting. Framework grains were counted for 300 to 350 counts per thin section; recalculated modal analysis data from point counting of the framework grains are listed in Table 2.

Chemical analyses (major elements) of nine selected samples (finer sandstones from the three wells were selected because they are likely to provide better geochemical results than the coarser grained rocks) were performed by X-ray fluorescence (XRF) spectrometry technique on fused beads (Rollinson, 1993), at the laboratories of the Geological Society of Iran (Table 3). Analytical precision is better than 3% for the major oxides. Relative errors on major elements are usually <2% and loss on ignition (LOI) was determined by heating the dried samples to 950 °C for 2 hours. Moreover, the total iron is expressed as Fe_2O_3.

DETRITAL FRAMEWORK COMPONENTS AND CLASSIFICATION

The detrital framework grains of the Ahwaz Sandstone Member include quartz, feldspars, rock fragments and accessory minerals such as zircon and sphene. By studying the texture of these sandstone we observed that fine grains are angular, and coarser ones are rounded to broken rounded. This occurs because in a high-energy environment or through long-distance transport, the well-sorted, coarse-grained sands not only round completely, but also break to fine-grained, angular sands, which results in a decrease of the sediment sorting. Although chemical mechanisms can round the grains by corroding them, these mechanisms round the fine-grained sands more than the coarser ones (more exposed surface in fine-grained particles), which is not the case in this study. Therefore, the heterogeneous roundness of grains for different grain sizes in the Ahwaz Sandstone reflect the importance of mechanical factors for the final grain shapes.

Quartz is the dominating framework grain in the studied thin sections (Figure 3a-d; also see Table 2). Monocrystalline quartz (Qm) occurs in three variants: non-undulose, slightly undulose (<5°), and undulose (>5°) (Scholle, 1979; Basu, 1985; Tortosa *et al.*, 1991). The polycrystalline quartz (Qpq) was distinguished into two groups: polycrystaline quartz with 2-3 subgrains and polycrystalline quartz with more than 3 subgrains (Figure 3b). Chert was considered as a monomineral (Folk, 1974) and was found only in a few samples. Some of the non-undulatory monocrystalline quartz contain inclusions of apatite and rutile needles, which could have been derived from plutonic source rocks or sedimentary recycling (Figure 3c-d).

Table 1. Key for petrographic and other parameters used in this study (modified after Dickinson, 1985).

Qm non	Non-undulouse monocrystalline quartz
Qm un	Undulouse monocrystalline quartz
Qpq	Polycrystalline quartz
Qpq>3	Qpq>3 crystal units per grain
Qpq2-3	Qpq2-3 crystal units per grain
Cht	Chert
Qp	Polycrystalline quartzose (or calcedonic) lithic fragments (Qpq + Cht)
Qt	Total quartzose grains (Qm + Qp)
Q	Total (Qm non + Qm un) and Qpq used for Folk (1980) classification (Qm + Qpq)
P	Plagioclase feldspar
K	Potassium feldspar
F	Total feldspar grains (P + K)
Lv	Volcanic-metavolcanic rock fragments
Ls	Sedimentary rock fragments
Lsm	Metasedimentary rock fragments
Lc	Carbonate (reworked fossils and limeclasts include mudstone) rock fragments
L	Unstable (siliciclastic) lithic fragments (Lv + Ls + Lsm)
Lt	Total siliciclastic lithic fragments (L + Qp)
RF	Total unstable rock fragments and chert used for Folk (1980) classification
Bio	*In situ* bioclast
Acc	Accessory minerals
Cc	Calcite (micrite and sparite)
Dc	Dolomite (dolomicrite and dolosparite)
Ac	Anhydrite cements

All studied thin sections contain small amounts of potassium feldspar (K), including twinned microcline. Furthermore, the low potassium values (mean value for $K_2O=0.94\pm0.40\%$; n=9) of the bulk rock analyses of sandstone samples, support the results of the petrography concerning the low K-feldspar content (Table 3). Plagioclase occurs in some thin sections and seems to be linked to samples with smaller grain sizes (fine-grained sand). Petrographic study of these sandstones reveals that K-feldspar is more abundant than plagioclase, which can be originated from durability of K-feldspars, non-occurrence of plagioclase-bearing source rocks, or both. The feldspars are fresh, which implies limited chemical weathering.

The thin sections contain lesser amount of lithic fragments than quartz and feldspar grains. Lithoclasts found in the studied samples include: siltstones, sandstones, carbonate fragments (rare), and metamorphic fragments. Volcanic fragments are absent in these sandstones.

Metamorphic lithoclasts are usually made up of metamorphic polycrystalline quartz fragments of high-grade metamorphic origin. The recrystallized subcrystals of a metamorphic polycrystalline quartz are lengthened and display different extinction angles under crossed polars due to the variable orientation of the C-axis (Scholle, 1979). Typical source rocks for these lithoclasts would be gneisses (Scholle, 1979).

A limited range of heavy minerals was observed in thin section. The most common is zircon, which occurs as well-rounded grains (Figure 3e). Other heavy minerals observed in thin-section include tourmaline and rutile. Also, re-sedimented quartz grains with thin, rounded, syntaxial relictic rims of quartz cement (Figure 3f) are common. Calcite and dolomite occur in the well-cemented sandstone samples.

Using Folk (1974) classification (QFL ternary plot), the Ahwaz Sandstone samples were classified as quartzarenite, sublitharenite and subarkose, thus reflecting their slightly mineralogical matured character (Figure 4). The geochemical classification diagrams of Pettijohn *et al.* (1972) and Herron (1988) for these sandstones (Figure 5) provide the same results.

PARENT ROCK LITHOLOGY

Because of the low abundance of feldspars, rock fragments and heavy minerals (Table 2), recognition of the source rock lithology of the Ahwaz Sandstone was established mainly by the study of quartz types.

Petrographic analysis of the thin sections shows small

Table 2. Detrital modes of selected samples of the Ahwaz sandstone member, Asmari Formation, Zagros, Iran.

Sample	Qpq	Qm	Qp	Qt	Q	F	Lt	L	RF	Cem+matx	Mic	SP	Cht	Acc	PR	Bio	SUM
8908	9	147	9	156	156	7	18	9	9	150	0	54	0	1	19	5	348
8929	10	150	12	162	160	9	15	3	5	156	0	0	2	1	21	0	353
8936	11	126	13	139	137	8	17	4	6	175	0	0	2	2	18	0	347
8949	6	137	6	143	143	4	10	4	4	154	0	25	0	2	14	22	347
8959	11	196	14	210	207	8	19	5	8	98	0	0	3	2	20	0	345
9014	12	160	15	175	172	5	19	4	7	120	0	0	3	1	41	10	358
9054	7	108	10	118	115	6	14	4	7	210	0	0	3	0	30	0	370
9056	7	109	10	119	116	7	15	5	8	213	0	0	3	0	17	0	362
9061’	11	147	13	160	158	5	16	3	5	143	0	0	2	2	24	0	339
9062	10	181	13	194	191	3	17	4	7	149	0	9	3	4	10	0	364
9072’	8	144	10	154	152	5	14	4	6	136	0	0	2	2	36	0	319
9075	5	140	7	147	145	9	12	5	7	160	44	35	2	0	12	15	352
9076’	7	148	7	155	155	9	11	4	4	150	32	16	0	2	24	10	354
9080’	12	146	15	161	158	5	19	4	7	145	0	0	3	2	23	0	342
9081’	8	121	10	131	129	7	16	6	8	147	0	20	2	2	24	5	324
9086’	10	133	11	144	143	5	15	4	5	171	42	63	1	2	9	16	353
9119’	11	137	14	151	148	8	19	5	8	174	0	0	3	1	10	0	351
9123’	10	117	12	129	127	6	16	4	6	189	0	0	2	2	21	0	352
9129’	9	139	11	150	148	5	15	4	6	173	0	0	2	2	15	0	351
9324	10	152	13	165	162	6	17	4	7	132	0	0	3	1	38	0	327
9344	11	141	13	154	152	7	18	5	7	170	0	0	2	0	29	7	274
9380	7	148	9	157	155	4	13	4	6	165	0	0	2	0	17	0	347
9425	12	147	15	162	159	7	20	5	8	160	0	0	3	1	15	0	351
9505’	8	121	10	131	129	8	14	4	6	180	0	0	2	0	23	0	246
9522	9	156	9	165	165	6	14	5	5	151	0	0	0	1	18	13	243
2692	13	132	15	147	145	5	17	2	4	105	20	0	2	0	5	65	338
2700	11	146	11	157	157	11	13	2	2	125	0	57	0	0	5	45	353
2709	25	148	27	175	173	4	28	1	3	109	49	60	2	0	4	85	380
2710	16	135	19	154	151	7	22	3	6	91	41	50	3	0	11	75	349
2807	11	123	12	135	134	4	14	2	3	110	0	35	1	1	15	68	362
2701	8	178	8	186	186	10	15	7	7	102	30	0	0	3	5	15	331
2639	16	171	16	187	187	6	18	2	2	130	0	0	0	0	15	0	341
2772	8	180	11	191	188	9	17	6	9	98	0	0	3	1	28	20	353
2782	9	128	12	140	137	8	16	4	7	162	0	50	3	0	29	0	304
2609	20	120	21	141	140	11	23	2	3	112	87	25	1	2	13	55	424
2854	11	220	11	231	231	8	18	7	7	89	0	0	0	3	9	0	348
2797	11	177	14	191	188	8	21	7	10	135	0	0	3	1	8	0	352
2855	11	202	16	218	213	11	24	8	13	100	0	0	5	5	5	0	347
2590	10	159	14	173	169	9	18	4	8	117	0	0	4	1	32	0	326
2592	5	150	9	159	155	8	15	6	10	142	0	30	4	0	30	0	345
2588	7	192	9	201	199	10	17	8	10	131	0	0	2	2	5	1	338
2670	8	191	10	201	199	11	15	5	7	116	0	0	2	2	20	0	355
2672	9	214	9	223	223	9	14	5	5	103	0	0	0	1	7	0	349
2679	7	192	8	200	199	7	14	6	7	119	0	81	1	1	9	0	345
2667	7	185	9	194	192	7	12	3	5	138	0	75	2	2	12	0	382
2608	207	9	216	216	1.3	9	17	8	8	93	0	0	0	2	15	0	350
2610	202	12	214	212	4.3	10	21	9	11	77	0	0	2	10	22	0	341
2618	178	7	185	184	5.2	6	12	5	6	119	0	0	1	3	27	0	242
2600	137	11	148	146	7.5	9	15	4	6	148	0	0	2	1	31	35	378
2620	162	8	170	170	4.2	8	14	6	6	151	20	15	0	2	30	0	278
All data (50 samples)																	
Average	27	139	30	167	147	7.3	16.5	4.7	6.5	138	7	14	1.9	1.5	18	11	
Std dev	51	51	54	28	55	2.1	3.4	1.8	2.2	31	18	23	1.3	1.7	10	22	
Minimum	5	7	6	118	1.3	3	10	1	2	77	0	0	0	0	4	0	
Maximum	207	220	216	231	231	11	28	9	13	213	87	81	5	10	41	85	
Selected data (after discordant outliers)																	
No. samples	43	50	44	50	45	50	49	50	50	50	8	17	39	35	50	19	
Average	9.5	139	11.7	167	163	7.3	16.2	4.7	6.5	138	35	41	2.4	1.7	18	30	
Std dev	2.4	51	3.1	28	27	2.1	3.0	1.8	2.2	31	11	22	0.9	0.7	10	27	
Minimum	5	7	6	118	115	3	10	1	2	77	20	9	1	4	4	1	
Maximum	16	220	21	231	231	11	24	9	13	213	49	81	5	1	41	85	

Note: Following the suggestion of Verma *et al.* (2008), these data were tested for possible discordant outliers under a normal population model using discordancy tests (Barnett and Lewis, 1994) with the new, precise critical values given by Verma and Quiroz-Ruiz (2006a, 2006b), and the statistical results are presented separately for different distributions. The first set of statistics is for all samples (a total of 50) whereas the second set is for samples (see the number of measurements column) after applying single outlier discordancy tests. Multiple outlier tests could be applied in future or some else geological criteria could be used before applying statistical tests. Cem: cement (Cc+Dc+Ac); matx: matrix; Mic: micrite; SP: sparite; PR: porosity; Std dev: Standard deviation.

Table 3. Major oxide values (wt. %) of the selected sandstone samples of the Ahwaz sandstone member, Asmari Formation, Zagros, Iran, along with their modified chemical index of weathering (CIW'; Cullers, 2000).

Well	Sample	Al_2O_3	SiO_2	CaO	Fe_2O_3	K_2O	MgO	Na_2O	SO_3	LOI	MnO	TiO_2	P_2O_5	Total	CaO*	CIW'
Az 11	8930	0.8	76.2	5.8	2.2	0.7	3.6	0.2	0.2	9.4	0.01	0.1	0.1	99.0	0.2	69.8
Az 11	8951	1.0	72.0	7.4	1.1	1.0	4.9	0.3	0.8	10.7	0.01	0.2	0.2	99.3	0.3	70.0
Az 11	8950	0.8	65.4	10.1	0.8	0.8	3.3	0.2	8.0	10.0	0.01	0.1	0.1	99.6	0.2	67.9
Az 11	9073	2.4	76.3	4.7	1.8	1.2	2.9	0.4	0.3	8.7	0.02	0.3	0.3	99.0	0.4	79.2
Az 11	9510	1.1	71.5	6.5	1.5	0.7	2.4	1.4	3.9	10.4	0.02	0.1	0.1	99.6	1.4	32.6
Az 89	2644	4.0	62.2	8.1	2.0	1.9	1.7	0.7	9.8	9.2	0.01	0.3	0.3	99.8	0.7	78.9
Az 89	2693	1.5	63.2	10.1	1.0	0.8	2.3	0.4	9.6	10.4	0.01	0.1	0.1	99.3	0.4	72.4
Az 89	2612	0.8	71.5	8.5	0.8	0.6	4.9	0.4	0.2	12.3	0.01	0.1	0.1	99.9	0.4	51.7
Az 85A	2861	2.5	69.2	8.0	1.8	0.8	4.4	0.5	1.0	11.3	0.02	0.3	0.3	99.7	0.5	76.1

CIW´ = molecular [Al_2O_3/ (Al_2O_3 + Na_2O)]×100; although average CIW´ value is quoted in the text, the data were not tested for possible discordant outlier using the methodology (Verma and Quiroz-Ruiz, 2006a, 2006b; Verma *et al.*, 2008). CaO* is defined as CaO in silicates only. Molecular CaO was first subtracted for phosphate using molecular P_2O_5 and then corrected by assuming reasonable Ca and Na fractions for sedimentary rocks. If CaO<Na_2O, then the molecular CaO is accepted as approximate CaO*; if, however, CaO>Na_2O, then CaO* was assumed to be equivalent to molecular Na_2O (McLennan, 1993). LOI: Loss on ignition.

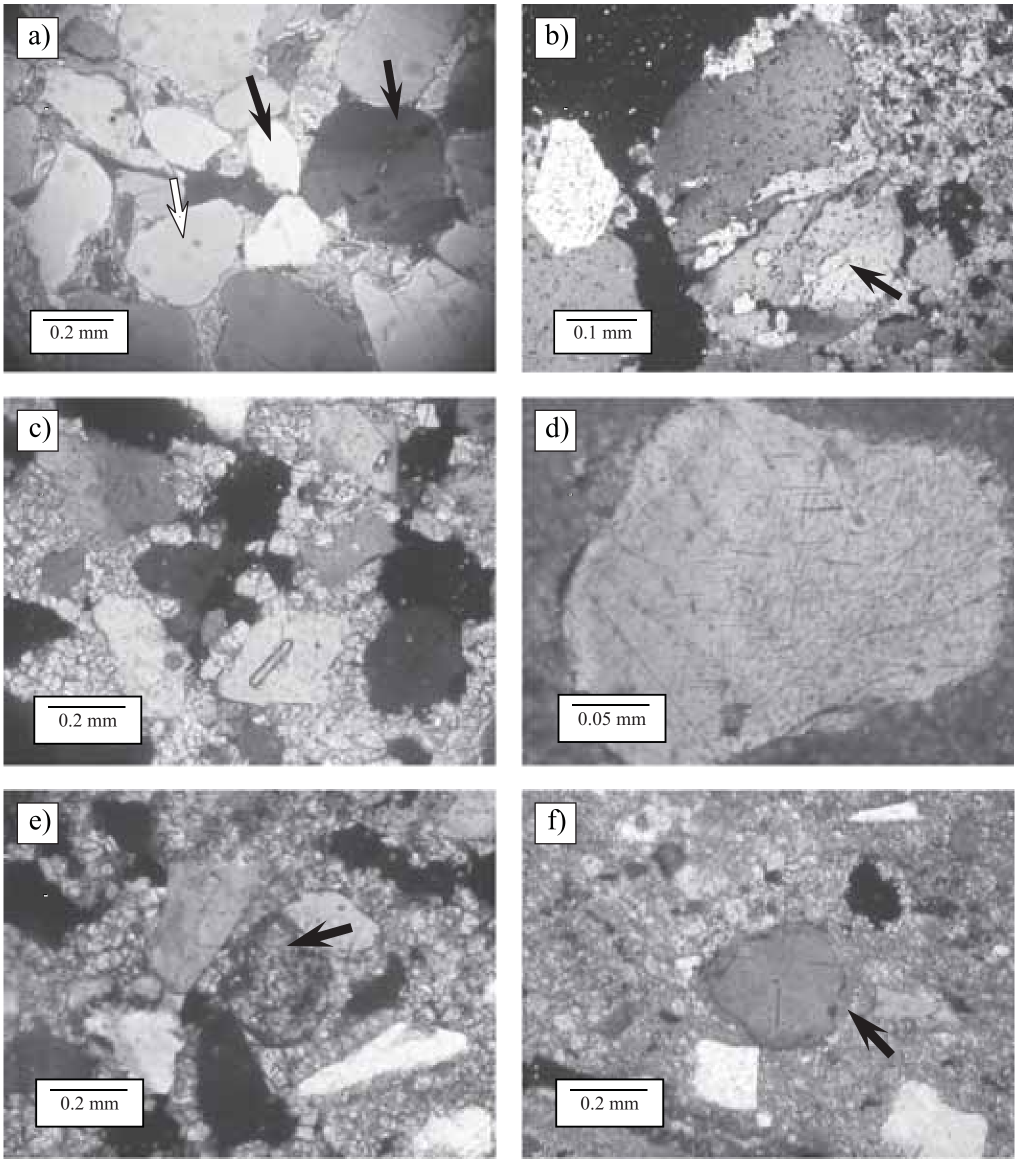


Figure 3. a: Photomicrograph showing quartz grains consisting mainly of monocrystalline quartz grains with undulose extinction (black arrow) and straight extinction (white arrow); b: polycrystalline quartz grain exhibiting a number of individual crystals with straight to slightly curved intercrystal boundaries; c: quartz grain including an apatite inclusion; d: quartz grain including inclusions of rutile needles; e: rounded grain of zircon as indicator of recycling; and f: rounded syntaxial relictic rims of quartz cement.

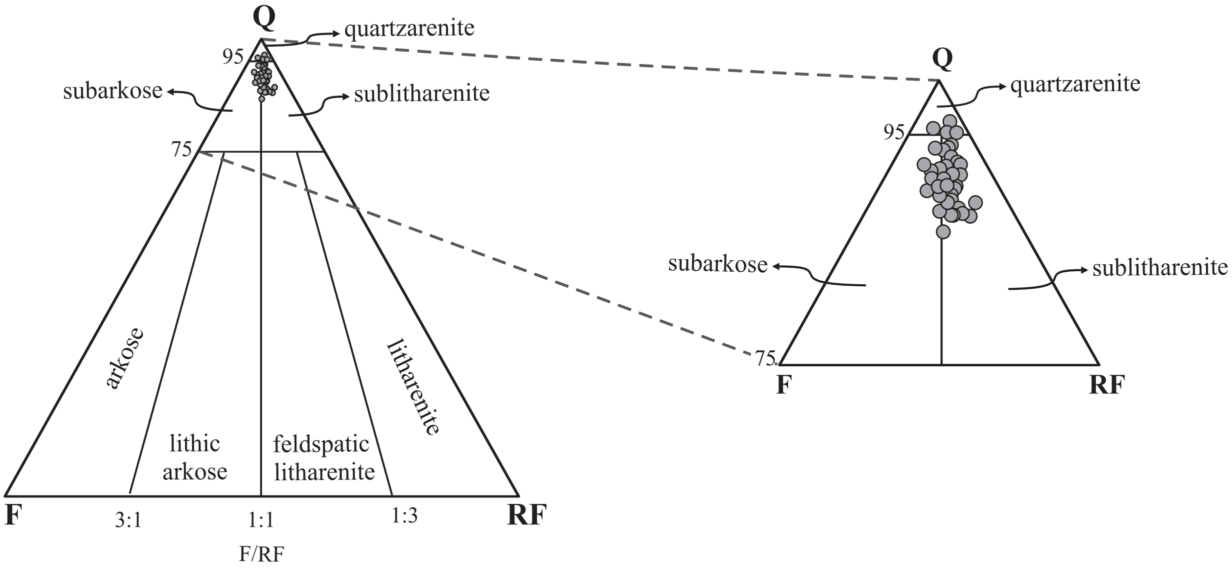


Figure 4. QFR triangular classification plot (Folk, 1974) of different sandstone samples from the Ahwaz sandstone member.

percentages of polycrystalline quartz grains (Table 2), which are of two types: the first type correspond to polycrystalline grains composed of five or more crystals with straight to slightly curved intercrystalline boundaries. The second type consists of polycrystalline quartz grains composed of more than five elongated crystals, exhibiting irregular to crenulated intercrystal boundaries (Figure 3b). The first type suggests an origin for the Ahwaz Sandstone from plutonic igneous rocks (Folk, 1974; Blatt *et al.*, 1980), while the second type indicates an origin from metamorphic source rocks (Blatt *et al.*, 1980; Asiedu *et al.*, 2000). Moreover, the Ahwaz Sandstone consists of monocrystalline quartz grains showing strong undulatory extinction and crypto-polycrystalline quartz grains, both suggestive of metamorphic source rocks. Nevertheless, the presence of strain-free quartz grains suggests plutonic source rock (*e.g.*, Basu, 1985).

To evaluate the relative importance of plutonic and metamorphic rocks as quartz sources, we plotted polycrystalline quartz *vs.* non-undulatory and undulatory monocrystalline quartz in a double-triangular diagram following the technique of Basu *et al.* (1975) and Tortosa *et al.* (1991) (Figure 6). These approaches give dramatically different results; a medium to low metamorphic origin and a granitic source rocks. These contrasting results can be partially explained by considering that the Ahwaz Sandstone samples plot in a region of the diagram where only some of the granite sourced modern sands analyzed by Tortosa *et al.* (1991) plot. In contrast, the North American sands studied by Basu *et al.* (1975) do not contain comparable quartz populations. Furthermore, Weltje *et al.* (1998) diagram shows that the point count data from the Ahwaz Sandstone plot in the arrow-shaped fields (Figure 7a) at the middle of the diagram, which represents a mixture of metamorphic and plutonic source rocks.

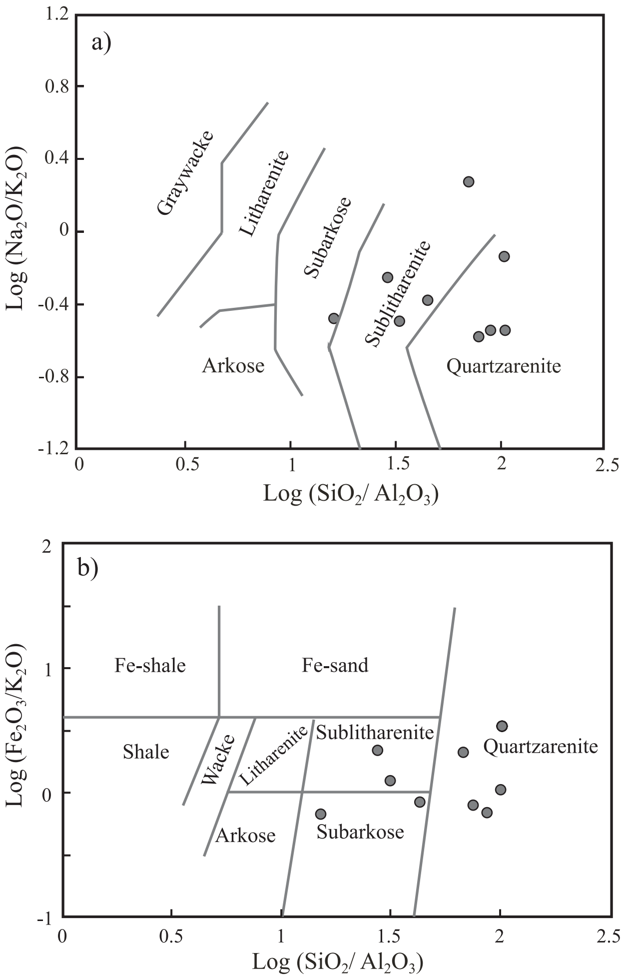


Figure 5. Chemical classification of samples from the Oligocene–Miocene Ahwaz sandstone member of the Asmari Formation based on (a) log (SiO_2/Al_2O_3) *vs.* log (Na_2O/K_2O) diagram of Pettijohn *et al.* (1972), and (b) the log (SiO_2/Al_2O_3) *vs.* log (Fe_2O_3/K_2O) diagram of Herron (1988).

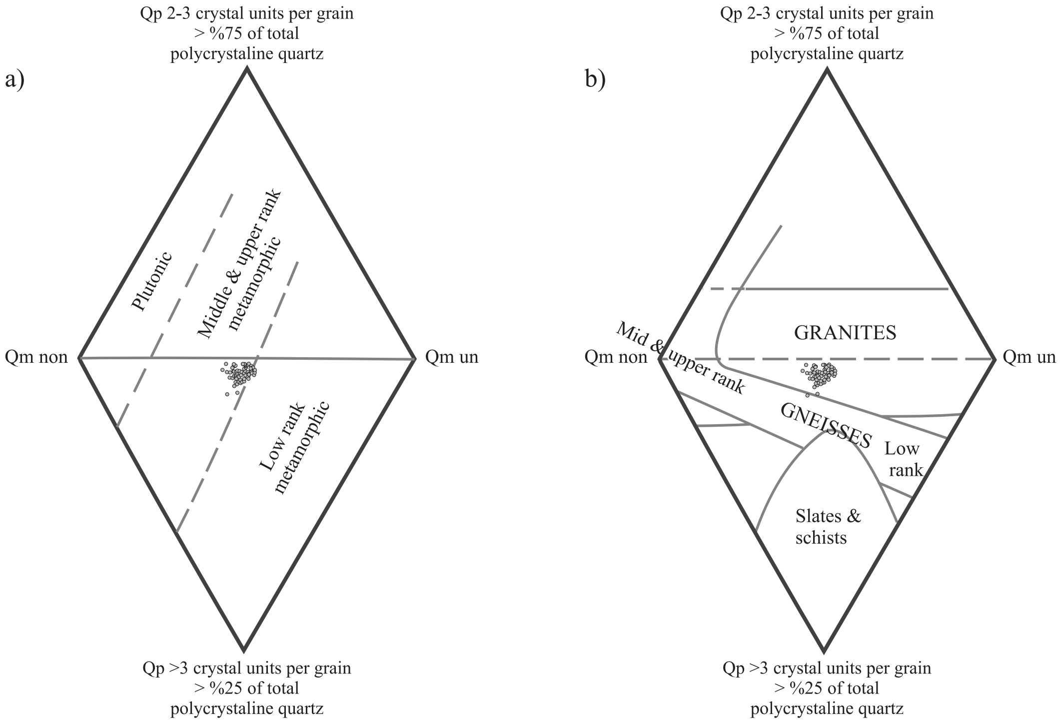


Figure 6. Varietal quartz diamond plot currently used to discriminate sands sourced by different types of crystalline rocks, on the basis of the extinction pattern and polycrystallinity of quartz grains. $Q_m$non: low-undulosity monocrystalline quartz grains; $Q_m$un = high-undulosity monocrystalline quartz grains; Qp2–3 = coarse-grained polycrystalline quartz grains; Qp > 3 = fine-grained polycrystalline quartz grains. Ahwaz sandstones are compared with provenance fields after Tortosa *et al.* (1991) and Basu *et al.* (1975) (diagrams b and a, respectively).

The effect of source rock on the composition of the Ahwaz Sandstone could be distinguished by plotting the point count data on Suttner *et al.* (1981) diagram (Figure 8). This approach also point to a metamorphic source rock for these sandstones.

In the Ahwaz Sandstone samples, most quartz grains are colorless and may include crystals of zircon or apatite (plutonic origin) (Figure 3c). However, a few quartz grains are dusty because of a profusion of rutile needle inclusions, and generally do not contain any other mineral inclusions (Figure 3d), which is typical of granulite-facies rocks.

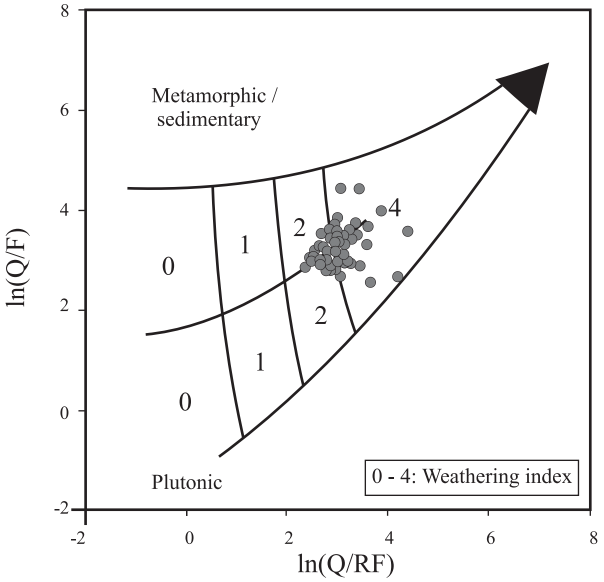
Accordingly, the monocrystalline (Basu *et al.*, 1975; Tortosa *et al.* 1991) and polycrystaline quartz grain characteristics (Folk, 1974; Blatt *et al.*, 1980; Asiedu *et al.*, 2000) as well as the logarithmic ratios of quartz to feldspars and rock fragments (diagram introduced by Weltje *et al.*, 1998) (Figure 7a) and quartz grain inclusions imply a mixed origin from plutonic and medium- to high-grade metamorphic rocks for the Ahwaz Sandstone. Furthermore, the evidence of recycling (rounded zircon and rounded overgrowths in some quartz grains) (Figure 3e-f) in the studied samples, indicate that quartz-rich sedimentary rocks should be considered as one of the major source rocks.

In order to use major elements for provenance interpretations we considered the discriminant functions of Roser and Korsch (1988), which use Al_2O_3, TiO_2, $Fe_2O_3^t$, MgO, CaO, Na_2O, and K_2O contents as variables. In this diagram (Figure 9), the majority of the Ahwaz Sandstone samples plot on the quartzose sedimentary provenance field. This is equivalent to a passive margin tectonic setting (Bathia, 1983).

TECTONIC PROVENANCE

In the QtFL and QmFLt ternary diagrams of Dickinson *et al.* (1983), the point counting data plot in the craton interior and recycled orogen (quartzose recycled) field (Figure 10). As pointed out by Dickinson *et al.* (1983), sandstones plotting in the craton field are mature sandstones derived from relatively low-lying granitoid and gneissic sources, supplemented by recycled sands from associated platform or passive margin basins.

The major element geochemistry of the Ahwaz Sandstone samples (Table 3) is discussed in terms of ternary plots and discrimination diagrams to characterize the tectonic setting as proposed by Bhatia (1983) and Kroonenberg (1994). These diagrams show that the Ahwaz Sandstone was deposited in a passive continental margin (Figures 11c and 12). However, in the diagrams of Bhatia (1983; Figures 11a, 11b), the Ahwaz Sandstone samples are shifted to the right of the passive margin field because of secondary MgO enrichment related to dolomite cement. Other reason for this discrepancy may be the deficient functioning of these



Semi-quantitative weathering index			Physiography (relief)		
			High (mountains) 0	Moderate (hills) 1	Low (plains) 2
Climate (precipitation)	(Semi) Arid and mediterranean	0	0	0	0
	Temperate subhumid	1	0	1	2
	Tropical humid	2	0	2	4

Figure 7. Log-ratio plot after Weltje *et al.* (1998). Q: quartz, F: feldspar, RF: rock fragments. Fields 1-4 refer to the semi-quantitative weathering indices defined on the basis of relief and climate as indicated in the table.

diagrams as documented by Armstrong-Altrin and Verma (2005). The high-MgO contents of the studied samples (average 3.4%) appear to be largely derived from dolomite (Von Eynatten, 2003), although the expected positive correlation between MgO and CaO, and between MgO and LOI was not statistically valid at 99% (or even at 95%) confidence level (using the computer program OYNYL by Verma *et al.*, 2006a).

SOURCE AREA WEATHERING

Climate indexes

Petrographic evidence such as heterogeneous roundness for different grains (coarser ones are rounded and finer ones are angular) implies the importance of mechanical effects for grain shape configuration. Coarse-grained feldspars are related to a low degree of chemical weathering. Moreover, the rounded quartz overgrowths indicate recycling, which, in turn, can modify the compositional data towards the quartz-rich sandstones. Therefore, the petrographic evidence suggests that the compositional maturity of these sandstones may be due to recycling and long transport on low-relief Arabian craton as has already been indicated by Ziegler (2001) and may not be related to a humid climatic condition.

The point count data for most Ahwaz Sandstone

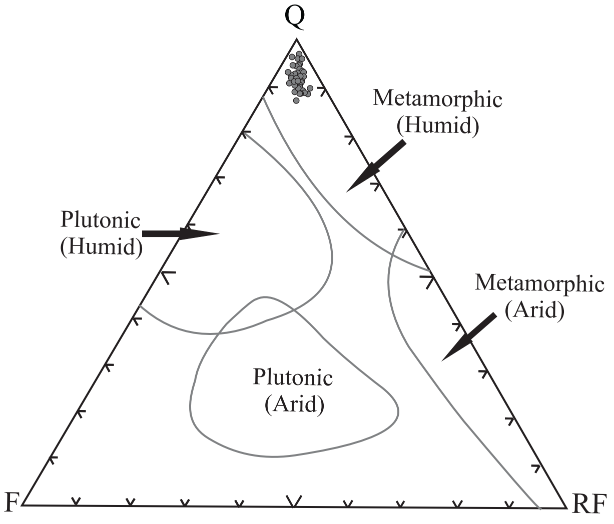


Figure 8. The effect of source rock on the composition of the Ahwaz sandstone using Suttner *et al.* (1981) diagram.

samples on Weltje *et al.* (1998) diagram plot in the field number 4 (Figure 7b), which points to the sedimentation in a low-relief and tropical, humid climatic conditions. The samples plotting in the field number 2 were either deposited on a low-relief with a temperate and sub-humid climate or on tropical, humid conditions within an area with a moderate relief. The diagram of Suttner *et al.* (1981) (Figure 8), however, indicate a metamorphic source rock in a humid climate. However, this particular diagram can discriminate only sources of metamorphic and plutonic rocks (humid or arid conditions) and does not discriminate between different tectonic settings. The diagrams (Figures 7b and 8) are defined for first-cycle sediments and the effect of recycling and long distance transportation can shift the data on these diagrams toward the humid conditions. These considerations probably imply that new diagrams should be proposed such as those suggested in the field of sedimentary rock geochemistry (Armstrong-Altrin and Verma, 2005) and already proposed in the area of igneous rock geochemistry (*e.g.*, Agrawal *et al.*, 2004; Verma *et al.*, 2006b).

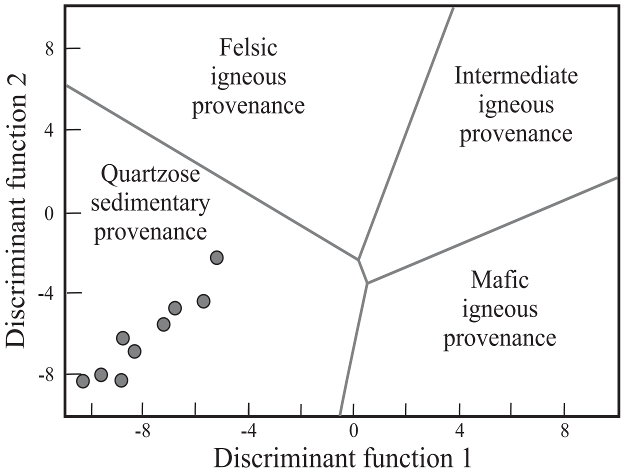


Figure 9. Discriminant function diagram for the provenance signatures of the Ahwaz Sandstone member using major elements. Boundaries between different fields are taken from Roser and Korsch (1988). These were designed to discriminate among four sedimentary provenances: mafic, P1: ocean island arc; intermediate, P2: mature island arc; felsic, P3: active continental margin; and recycled, P4: granitic–gneissic or sedimentary source (Roser and Korsch, 1988).

Geochemistry and source area weathering

Alteration of rocks during weathering results in depletion of alkalis and alkaline earth elements and preferential enrichment of Al_2O_3 (*e.g.*, Cingolani *et al.*, 2003). Therefore, weathering effects can be evaluated in terms of the molecular percentage of the oxide components, using the formulae of chemical index of weathering (CIW = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O]\times100$; Harnois, 1988) and chemical index of alteration (CIA= $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O]\times100$); Nesbitt and Young, 1982). However, samples having highly variable CaO contents due to variation in calcite or dolomite abundance (such as those included in this study), may produce misleading conclusions if the CIW and CIA are used to infer the degree of weathering (Cullers, 2000). Therefore, in this study we used a modified chemical index of weathering (CIW´ = molecular $[Al_2O_3/ (Al_2O_3 + Na_2O]\times100$, in which CaO is left out of the CIW; Cullers, 2000). The CIW´ value of the Ahwaz Sandstone samples vary from 32 to 79 (*n*=9, mean ~67, *s*=15; median ~70), which indicate a moderate weathering (recycling) for these sandstones. These CIW´ values, in general, can be due to either absence of intense recycling in a humid climate or intense recycling in an arid/semiarid climate (Osae *et al.*, 2006; Wanas and Andel-Maguid, 2006).

Petrographic evidence from the Ahwaz Sandstone (heterogeneous roundness for different grain sizes; fresh

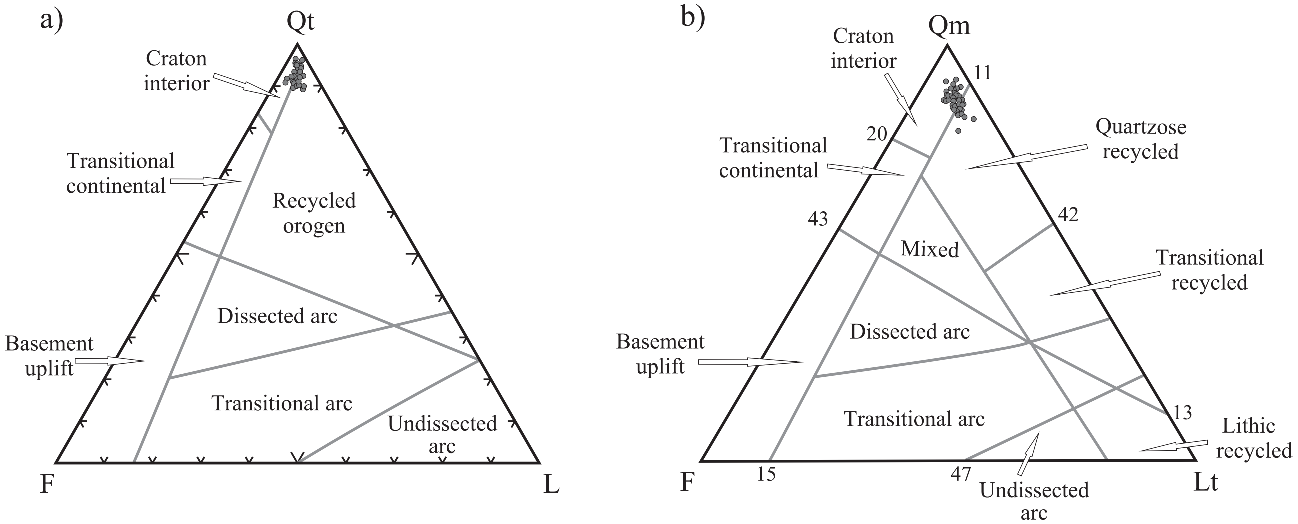


Figure 10. (a) QtFL and (b) QmFLt ternary diagrams for the Ahwaz sandstone, after Dickinson *et al.* (1983).

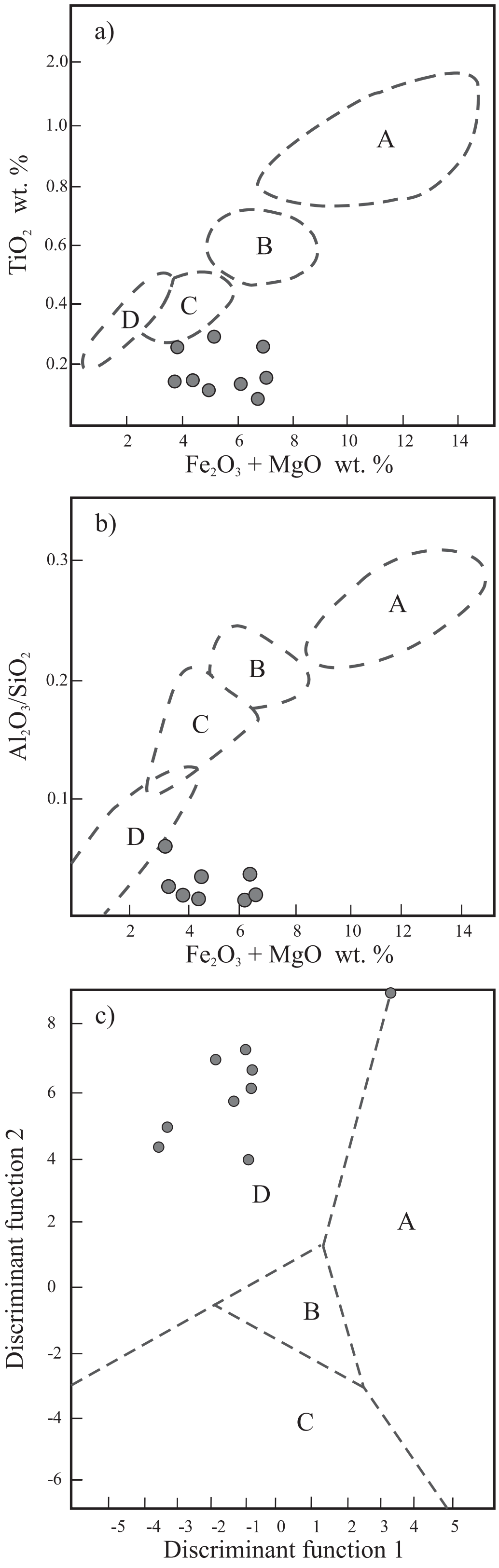


Figure 11. Plots of the major element composition of the Ahwaz Sandstone on the tectonic setting discrimination diagrams of Bhatia (1983). a: Fe$_2$O$_3$t+ MgO *vs.* TiO$_2$; b**:** Fe$_2$O$_3^t$+MgO *vs.* Al$_2$O$_3$/SiO$_2$; c: discrimination diagram. A: Oceanic island Arc, B: continental island Arc, C: active continental margin, D: passive margin.

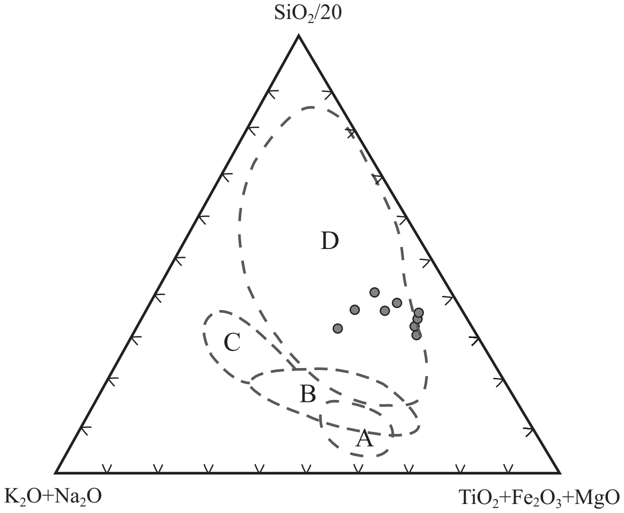


Figure 12. Plot of the major element composition of the Ahwaz Sandstone on the tectonic setting discrimination diagram of Kroonenberg (1994). Field labels as in Figure 10.

coarse-grained feldspars) is consistent with a more important role for mechanical weathering than for chemical weathering. Similarly, petrographic evidence of rounded quartz overgrowths can be related to an intense recycling of their source rock. The geochemical (Figure 9) and point count (Figure 10) data as well as CIW´ values are consistent with an active recycling in an arid/semiarid climate for Ahwaz Sandstone. However, more accurate interpretation of climate conditions of these deposits would require further studies such as clay mineral investigations.

CONCLUSIONS

Quartz arenites, sublitharenite and subarkose of the Ahwaz Sandstone (sandy member of Asmari Formation, the major oil reservoir in Zagros mountain) have petrographic (texture, framework mineralogy, quartz types and inclusions in quartz) and geochemical characteristics that suggest quartzose recycled sedimentary rocks as the main source rocks, in addition to high-grade metamorphic and plutonic igneous rocks as minor parent rocks. Moreover, the obtained data are consistent with a long distance transport, in an arid/semiarid climate, over the Arabian shield, which supplied these sands to their depositional basin along the passive marginal coast of the Oligocene-Miocene Zagros foreland basin.

ACKNOWLEDGMENTS

We thank the National Iranian Oil Company, especially H. Ghalavand for providing us with the core samples and thin sections, and the Shahid Beheshti University of Tehran for providing laboratory equipments. In addition, we are grateful to M.H. Adabi for his considerable help throughout this study. We would like to thank J.S. Armstrong-Altrin and an anonymous reviewer for helpful and constructive reviews. The manuscript has largely been improved by constructive comments and corrections from the RMCG editor, Dr S.P. Verma.

REFERENCES

Agrawal, S., Guevara, M., Verma, S.P., 2004, Discriminant analysis applied to establish major element field boundaries for tectonic varieties of basic rocks: International Geology Review, 46(7), 575-594.

Alavi, M., 2004, Regional stratigraphy of the Zagros fold-thrust belt of Iran and its proforeland evolution: American Journal of Science, 304, 1–20.

Alsharhan, A.S., Nairn, A.E.M., 1997, Sedimentary Basins and Petroleum Geology of the Middle East: Amsterdam, Elsevier, 843 p.

Armstrong-Altrin, J.S., Verma, S.P., 2005, Critical evaluation of six tectonic setting discrimination diagrams using geochemical data of Neogene sediments from known tectonic settings: Sedimentary Geology, 177(1-2), 115-129.

Armstrong-Altrin, J.S., Lee, Y.I., Verma, S.P., Ramasamy, S., 2004, Geochemistry of sandstones from the Upper Miocene Kudankulam Formation, southern India: implication for provenance, weathering and tectonic setting: Journal of Sedimentary Research, 74(2), 285–297.

Asiedu, D.K., Suzui, S., Shibata, T., 2000, Provenance of sandstones from the Lower Cretaceous Sasayama Group, inner zone of southwest Japan: Sedimentary Geology, 131, 9–24.

Barnett, V., Lewis, T., 1994, Outliers in Statistical Data: Chichester, John Wiley, third edition, 584 p.

Basu, A., 1985, Reading Provenance from Detrital Quartz, *in* Zuffa, G.G. (ed.), Provenance of Arenites: Dordrecht, NATO ASI Series, C 148, D. Reidel Publishing Company, 231-247.

Basu, A., 2003, A perspective on quantitative provenance analysis, *in* Valloni, R., Basu, A. (eds.), Quantitative Provenance Studies in Italy: Memorie Descrittive Della Carta Geologica dell'Italia, 61, 11–22.

Basu, A., Young, S., Suttner, L., James, W., Mack, G.H., 1975, Re-evaluation of the use of undulatory extinction and crystallinity in detrital quartz for provenance interpretation: Journal of Sedimentary Petrology, 45, 873–882.

Berberian, M., King, G.C.P., 1981, Towards the paleogeography and tectonic evolution of Iran: Canadian Journal of the Earth Sciences, 18, 210–265.

Beydoun, Z.R., Hughes Clarke, M.W., Stoneley, R., 1992, Petroleum in the Zagros basin: A Late Tertiary foreland basin overprinted onto the outer edge of a vast hydrocarbon-rich Palaeozoic–Mesozoic passive margin shelf: American Association of Petroleum Geologists, Memoir, 55, 309–339.

Bhatia, M.R., 1983, Plate tectonics and geochemical composition of sandstones: Journal of Geology, 91, 611–627.

Bhatia, M.R., Crook, K.A.W., 1986, Trace element characteristics of greywackes and tectonic setting discrimination of sedimentary basins: Contributions to Mineralogy and Petrology, 92, 181–193.

Blatt, H., Middleton, G., Murray, R., 1980, Origin of Sedimentary Rocks: Prentice-Hall, New Jersey.

Buck, S.G., 1991, Ahwaz Reservoir Characterization Study: Schlumberger-National Iranian Oil Company (unpublished).

Chittleborough, D.J., 1991, Indices of weathering for soils and palaeosols formed on silicate rocks: Australian Journal of Earth Sciences, 38, 115–120.

Cingolani, C.A., Manassero, M., Abre, P., 2003, Composition, provenance, and tectonic setting of Ordovician siliciclastic rocks in the San Rafael block: Southern extension of the Precordillera crustal fragment, Argentina: Journal of South American Earth Sciences, 16(1), 91-106.

Crook, K.A.W., 1974, Lithogenesis and geotectonics: the significance of compositional cariations in flysch arenites (graywackes), *in* Dott, R.H., Shaver, R.H. (eds.), Modern and Ancient Geosynclinal Sedimentation: Society for Sedimentary Geology Special Publication, 19, 304–310.

Cullers, R.L., 2000, The geochemistry of shales, siltstones and sandstones of Pennsylvanian–Permian age, Colorado, USA: implications for provenance and metamorphic studies: Lithos, 51, 181–203.

Dickinson, W.R., 1985, Interpreting provenance relation from detrital modes of sandstones, *in* Zuffa, G.G. (ed.), Provenance of Arenites: NATO ASI Series, C 148, D. Reidel Publishing Company, Dordrecht, 333–363.

Dickinson, W.R., Suczek, C.A., 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologist, 63, 2164–2182.

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., Ryberg, P.T., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, 94, 222-235.

Folk, R.L., 1974, Petrology of Sedimentary Rocks: Austin, TX, Hemphill Press, second edition, 182 p.

Folk, R.L., 1980, Petrology of Sedimentary Rocks: Austin, Texas, Hemphill, 159 p.

Harnois, L., 1988, The CIW index: A new chemical index of weathering: Sedimentary Geology, 55**,** 319–322.

Herron, M.M., 1988, Geochemical classification of terrigenous sands and shales from core or log data: Journal of Sedimentary Petrology, 58, 820–829.

Ingersoll, R.V., Bulard, T.F., Ford, R.L., Grimn, J.P., Pickle, J.P., Sares, S.W., 1984, The effect of grain size on detrital modes: a text of the Gazzi-Dickinson Point Counting method: Journal of Sedimentary Petrology, 54, 103-116.

Insalaco, E., Virgone, A., Courme, B., Gaillot, J., Kamali, M., Moallemi, A., Lotfpour, M., Monibi, S., 2006, Upper Dalan Member and Kangan Formation between the Zagros Mountains and offshore Fars, Iran: depositional system, biostratigraphy and stratigraphic architecture: Bahrain, Gulf PetroLink, GeoArabia, 11(2), 75-176.

Kroonenberg, S.B., 1994, Effects of provenance, sorting and weathering on the geochemistry of fluvial sands from different tectonic and climatic environments: Proceedings of the 29th International Geological Congress, Part A, 69-81.

Lacassagne, R.M., 1963, Asmari sedimentary Environment of southwest Iran: Iranian Oil Operating Companies, Geology and Exploration Division, Paleontology Department, 50 p.

McLennan, S.M., 1993, Weathering and global denudation: The Journal of Geology, 101, 295–303.

McLennan, S.M., Hemming, S., McDaniel, D.K., Hanson, G.N., 1993, Geochemical approaches to sedimentation, provenance and tectonics, *in* Johnsson, M.J., Basu, A. (eds.): Geological Society of America, Special Papers 285**,** 21–40.

Milodowski A.E, Zalasiewicz J.A, 1991, Redistribution of rare earth elements during diagenesis of turbidite/hemipelagic mudrock sequences of Llandovery age from central Wales, *in* Morton, A.C., Todd, S.P., Haughton, P.D.W. (eds.), Developments in Sedimentary Provenance Studies: Geological Society of London, Special Publication, 57, 101–124.

Motiei, H., 1993, Stratigraphy of Zagros, *in* Hushmandzadeh, A. (ed.), Treatise on the Geology of Iran: Tehran, Geological Survey of Iran, 536 p.

Nesbitt, H.W., Young, G.M., 1982, Early Proterozoic climates and plate motions inferred from major element chemistry of lutites: Nature, 299, 715–717.

Nesbitt, H.W., Young, G.M., 1989, Formation and diagenesis of weathering profile: Journal of Geology, 97, 129–147.

Osae, S., Asiedu, D.K., Banoeng-Yakubo, B., Koeberl, C., Dampare, S.B., 2006, Provenance and tectonic setting of Late Proterozoic Buem sandstones of southeastern Ghana: Evidence from geochemistry and detrital modes: Journal of Asian Earth Sciences, 44, 85-96.

Pettijohn, F.J., Potter, P.E., Siever, R., 1972, Sand and Sandstones: New York, Springer-Verlag.

Rollinson, H.R., 1993, Using Geochemical Data: Evaluation, Presentation, Interpretation: United Kingdom, Longman, 352 p.

Roser, B.P., Korsch, R.J., 1986, Determination of tectonic setting of sandstone–mudstone suites using SiO_2 content and K_2O/Na_2O ratio: Journal of Geology, 94, 635–650.

Roser, B.P., Korsch, R.J., 1988, Provenance signatures of sandstone–mudstone suites determined using discriminant function analysis of major-element data: Chemical Geology, 67, 119–139.

Scholle, P.A., 1979, A Color Illustrated Guide to Constituents, Textures, Cements, and Porosities of Sandstones and Associated Rocks: Tulsa, Oklahoma, American Association of Petroleum Geologists, Memoir, 28, 201 p.

Seyrafian, A., 2000, Microfacies and depositional environment of the Asmari Formation at Dehdez area (A correlation across Central Zagross Basin): Carbonates and Evaporites, 15, 22-48.

Shanmugam, G., 1985, Type of porosity in sandstone and their significance in interpreting provenance, *in* Zuffa, G.G. (ed.), Provenance of Arenites: Dordrecht, NATO ASI Series, C 148, D. Reidel Publishing Company, 115-138.

Stocklin, J., 1974, Possible ancient continental margins in Iran, *in* Burk, C.A., Drake, C.L. (eds.), The Geology of Continental Margins: New York, Springer, 873–887.

Suttner, L.J., Basu, A., Mack, G.H., 1981, Climate and the origin of quartz arenites: Journal of Sedimentary Petrology, 51, 235-246.

Taylor, S.R., McLennan, S.M., 1985, The continental crust: its composition and evolution: Oxford, Blackwell, 312 p.

Tortosa, A., Palomares, M., Arribas, J., 1991, Quartz grain types in Holocene deposits from the Spanish Central System: some problems in provenance analysis, *in* Morton, A.C., Todd, S.P., Haughton, P.D.W. (eds.), Developments in Sedimentary Provenance Studies: Geological Society of London, Special Publication, 57, 47– 54.

Valloni, R., Mezzardi, G., 1984, Compositional suites of terrigenous deepsea sands of the present continental margins: Sedimentology, 31, 353–364.

Van der Plas, L., Tobi, A.C., 1965, A chart for judging the reliability of point counting results: American Journal of Science, 263, 87–90.

Vaziri-Moghaddam, H., Kimiagari, M., Taheri, A., 2006, Depositional environment and sequence stratigraphy of the Oligo-Miocene Asmari Formation in SW Iran: Facies, 52, 41-51.

Verma, S.P., Quiroz-Ruiz, A., 2006a, Critical values for six Dixon tests for outliers in normal samples up to sizes 100, and applications in science and engineering: Revista Mexicana de Ciencias Geológicas, 23(2), 133-161.

Verma, S.P., Quiroz-Ruiz, A., 2006b, Critical values for 22 discordancy test variants for outliers in normal samples up to sizes 100, and applications in science and engineering: Revista Mexicana de Ciencias Geológicas, 23(3), 302-319; with electronic tables available at http://satori.geociencias.unam.mx.

Verma, S.P., Díaz-González, L., Sánchez-Upton, P., Santoyo, E., 2006a, OYNYL: A new computer program for ordinary, York, and New York least-squares linear regressions: WSEAS Transactions on Environment and Development, 2(8), 997-1002.

Verma, S.P., Guevara, M., Agrawal, S., 2006b, Discriminating four tectonic settings: Five new geochemical diagrams for basic and ultrabasic volcanic rocks based on log-ratio transformation of major-element data: Journal of Earth System Science, 115(5), 485-528.

Verma, S.P., Quiroz-Ruiz, A., Díaz-González, L., 2008, Critical values for 33 discordancy test variants for outliers in normal samples up to sizes 1000, and applications in quality control in Earth Sciences: Revista Mexicana de Ciencias Geológicas, 25(1), 82-96, with 209 pages of electronic supplement 25-1-01 Critical values for 33 discordancy tests.

Von Eynatten, H., 2003, Petrography and chemistry of sandstones from the Swiss Molasse Basin: an archive of the Oligocene to Miocene evolution of the Central Alps: Sedimentology, 50, 703-724.

Wanas, H.A., Andel-Maguid, N.M., 2006, Petrography and geochemistry of the Cambro-Ordovician Wajid Sandstone, southwest Saudi Arabia: Implications for provenance and tectonic setting: Journal of Asian Earth Sciences, 27, 416-429.

Weltje, G.J., 2002, Quantitative analysis of detrital modes: statistically rigorous confidence regions in ternary diagrams and their use in sedimentary petrology: Earth-Science Review, 57, 211-253.

Weltje, G.J., Meijer, X.D., De Boer, P.L., 1998, Stratigraphic inversion of siliciclastic basin fills: a note on the distinction between supply signals resulting from tectonic and climatic forcing: Basin Research, 10, 129–153.

Zahedinezhad, J., 1987, Geological study of Ahwaz sandstone member in southern part of Asmari sedimentary basin: National Iranian Oil Company, Report No. 4028, 125 p.

Ziegler, M.A., 2001, Late Permian to Holocene paleofacies evolution of the Arabian plate and its hydrocarbon occurrences: Bahrain, Gulf Petrolink, Geo Arabia, 6(3), 445-505.

Zimmermann, U., Bahlburg, H., 2003, Provenance analysis and tectonic setting of the Ordovician clastic deposits in the southern Puna Basin, NW Argentina: Sedimentology, 50, 1079–1104.

Manuscript received: December 3, 2007
Corrected manuscript received: March 2, 2008
Manuscript accepted: March 3, 2008