



Geochemistry and Provenance of Mukdadiya Sandstone Formation, Eastern Iraq

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Abstract

Two surface sections of Mukdadiya Formation, namely Al-Band and Bajaliah in eastern Iraq, are selected to conduct the geochemistry of sandstone. Fifteen sandstone samples were analyzed by using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) and fused XRF techniques to determine the content of major oxides (SiO_2 , Fe_2O_3 , TiO_2 , Al_2O_3 , CaO , K_2O , Na_2O , SO_3 , L.O.I), trace elements (Cr, Ni, Co, V, Sc, Zr, Hf, Ta, Nb, Th, U, Y, Rb, Sr) and rare earth elements, REE (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu). SiO_2 versus $(\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O})$ diagrams indicated that Mukdadiya sandstone was deposited under arid to semi-arid paleo-climate conditions. The elemental ratios based on Cr, Ni, Co, V, and Sc indicate that andesite is a source rock of sandstone. Zr, Hf, Th, U, and Sr tend to increase in sand samples because of their high resistance to chemical weathering. Also, the Nb/Y vs Zr/TiO₂ diagram shows that the andesite is a source rock of Mukdadiya sandstone. Furthermore, the elemental ratios $\Sigma\text{LREE}/\Sigma\text{HREE}$, La_N/Lu_N , and Eu/Eu^* show an enrichment of LREE with the decrease in grain size and with an increase in clay contents in the sand samples. La-Th-Sc triangular discrimination diagram reveals that Mukdadiya sandstones are plotted in the continental arc field. The REE patterns indicated the contribution of both intermediate rock (andesite) and basic rock (basalt) igneous rocks to be the expected source of Mukdadiya sandstone.

Keywords:

Sandstone, Andesite, REE, Geochemistry, Chemical weathering.

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1. Introduction

The research area is situated in the Al-Teeb district at the northeastern part of Missan Governorate, close to the eastern international border between Iraq and Iran at the latitudes (32° 25' 51" N and 47° 13' 03" E and longitudes 32° 15' 36" N and 47° 27' 18" E (Fig.1). The study area is located in the Foothill Zone of the Unstable Shelf within the range of the low folded zone (Al-Mutury and Al-Asadi, 2008).

Mukdadiya Formation (Pliocene) is well exposed in the Foothill zone in the northwest of Missan Governorate. Mukdadiya was previously named Bakhtiari Formation according to Bellen et al. (1959), which was divided into lower and upper Formations; namely Mukdadiya and Bai Hassan nowadays (Jassim and Kareem, 1984). Mukdadiya Formation comprises fining-upwards cycles of

gravely sandstone, sandstone, and brown mudstone; the sandstones are often strongly cross-bedded and associated with channel lags and clay balls deposited in a fluvial environment in a rapidly subsiding foredeep basin (Jassim and Goff, 2006). The type section is near Al-Mukdadiya City in Diyala Governorate in the middle of Iraq, where the thickness of the formation is 1411m (Al-Rawi et al., 1992). Mukdadiya Formation has been studied in other parts of Iraq such as in Dohuk (Zawita and Amadya), Mosul, Tikrit, Dyala and Wasit by many researchers, for example: Al-Jassim (1969), who suggested that the formation was deposited in flood plain and alluvial lakes environments in central Iraq; Sadik (1977), who found that quartz and chert are dominated in Mukdadiya Formations; Al-Samaani (2011) who suggested that sources of Mukdadiya Formation sandstone are contribution of igneous,

metamorphic, and sedimentary sources and the provenance are mainly the old sediments located at northeastern part of Iraq; Al-Kalidi (2014) who suggests the semi-arid to semi-humid environments of immature to sub-mature sandstone of Mukdadiya Formation in Zawita and Amaadya areas in northeast of Iraq; Al-Dabbagh (2018) who reported that the sandstone of Mukdadiya Formation in Zurbatiya area (eastern Iraq) is classified as litharinite, sedarinite and calcilithite. The geochemistry of sandstone has been used to discriminate the tectonic setting of stream sediments (Jimoh et al., 2024; Odewumi and Shola, 2024).

The source rocks, tectonic setting, paleo weathering conditions, and paleoclimate of sandstone are sensitively indicated by the behavior of major elements and some trace elements like Sc, Zr, Co, Hf, Cr, Y, Th, including rare earth elements (REEs) and their elemental ratios (Bhatia and Crock, 1986; Rose and Crosch, 1988; Al-Juboury, 2009; Tobia and Aswad, 2014; Ali et al, 2017; Ali, 2021; Ramezani et al., 2022; and Kafy and Tobia, 2022). The current study aims to investigate the geochemical properties (major, trace, and REE) elements of Mukdadiya sandstone to determine their provenance, tectonic setting, and paleoenvironment of deposition.

2. Geological and Tectonic Setting

Missan area represents a part of the Makhul-Hemrine subzone (Low-Folded Zone) located outside the Arabian plate form (Jassim and Goff, 2006). Fouad (2008 and 2012); Abdulnaby et al. (2021). They stated that the typical environment of the Mukdadiya Formation is fluvial, which rapidly subsides in the foredeep basin. In the late Miocene-Pliocene period, major thrusting occurred during the collision of new Tethyan terrains and the Sanandaj-Sirjan zone with the Arabian plate, resulting in the uplift of highly folded, northern thrust zones, and the NE part of the Balambo-Tanjero zone in Iraq (Figs. 2 and 3)

There are multiple sedimentary cycles made up the Mukdadiya Formation in the study area; the majority of the ascending cycles are composed of conglomerates, sandstone, and claystone from the bottom to top. Different sizes of gravel and sand represent fining upward cycles reflecting fluvial environments. A variety of sedimentary structures, including channeling that is occasionally filled

with gypsum, trough cross-bedding, graded bedding, and planar cross-bedding. The upper contact of Mukdadiya with Bai Hassan's Formation is conformable, which is occasionally covered by Quaternary sediments, while the lower contact of Mukdadiya with the underlying Injana Formation is detected by pebbly sandstone. Large parts of the unstable shelf are covered by the majority of Quaternary sediments from the southern Iraqi Mesopotamian plain (Al- Khafaji and Mahdi, 2019)

3. Materials and Methods

Two sections in the Al-Band and Al-Bajalia areas are selected for lithological description and measuring the thickness of sandstone units, that conducted in the field (Fig. 1).

Spot samples method is used for collecting sandstone samples based on the variation in lithology, color, and thickness of beds. Grain size analysis of nine sandstone samples is carried out using classic sieving methods and pipette analyses. Folk method (1974) was used to separate mud from sand components. Furthermore, fifteen sandstone samples are analyzed by the fusion XRF technique model pw 1480 sequential spectrometer with KV=60, WA=40, Target= Chromium; and ICP-MS (inductively coupled plasma mass spectrometry) type Agilent 7700 series at Kansaran Binaloud Company, Iran to determine their content of major, trace, and REEs.

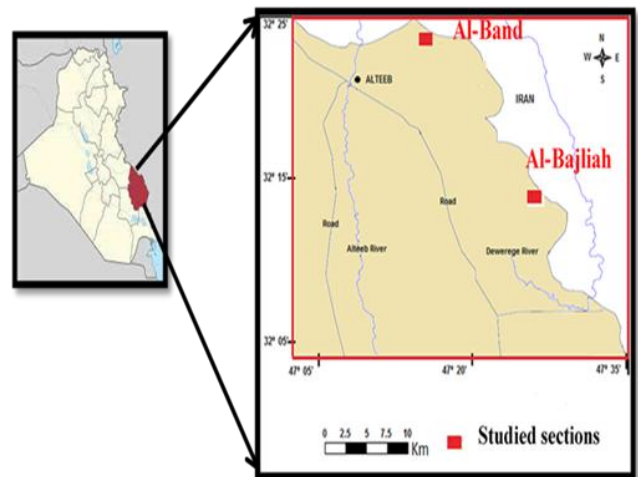


Fig. 1: Map of the studied area.

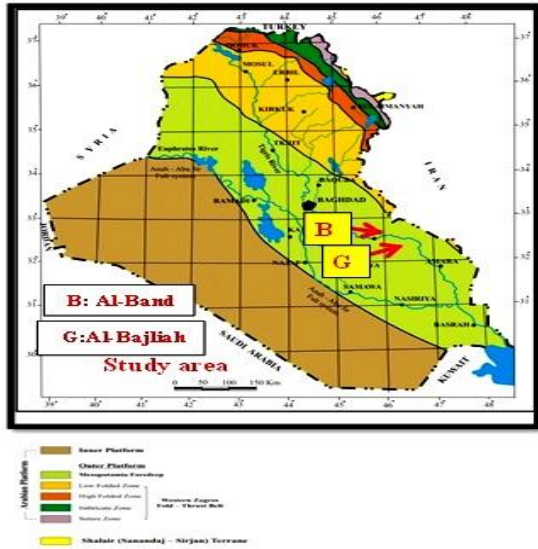


Fig. 2: Location and tectonic map of the study area (Fouad, 2012).

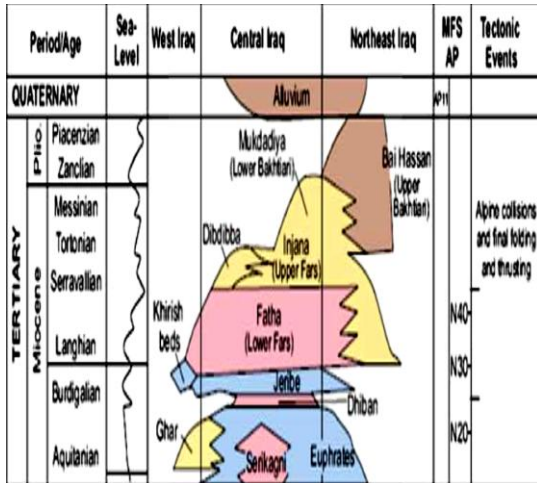


Fig. 3: Sequence interpretation and correlation in Iraq (Jassim and Goff, 2006) showing the location of Mukdadiya Formation in the succession.

4. Results and discussion

A. Grain size analysis

Nine sandstone samples, representing two sections (four from Al-Band section and five from Al-Bajaliah section), were collected to carry out the grain size analysis (Table 1; Figs. 4, 5, 6 and 7). In general, the major component is sand (58.5% average), followed by gravel (31.27% average) and mud (10.25% average) in the Al-Band section. The average sand percentage is 78.5%, followed by an average mud percentage of 12.36% and an average of 9.56% in the Al-Bajaliah section. The results show an increase in sand percentage and a decrease in gravel percentage in both sections. The differences in the averages for sand, gravel, and mud can be attributed to their relative distances from the source in northern Iraq. The distance from the source transport led to increases in the average sand content and reductions in the gravel content, especially in the Al-Bajaliah section.

Table 1: Alignment center and text wrapping none, the spacing is 1, and no spacing before and after.

Section	Grain size (Phi)	Gravel (< 1-)	Sand (-1- 4.0)	Mud (4.0 -10)	Total	Texture
Al-Band (B)	B(1)	28.3	61.4	10.3	100	gravelly muddy sand
	B(2)	36.9	55.1	8	100	gravelly muddy sand
	B(3)	34.5	53.9	11.6	100	gravelly muddy sand
	B(4)	25.4	63.6	11	100	gravelly muddy sand
	Average	31.275	58.5	10.225	100	
Al-Bajaliah	G(2)	6.2	90.7	3.1	100	sandstone
	G(5)	14.5	67.5	18	100	gravelly muddy sand
	G(8)	10.4	71.8	17.8	100	gravelly muddy sand
	G(10)	5.4	90.3	4.3	100	sandstone
	G(12)	11.3	70.1	18.6	100	gravelly muddy sand
Average	9.56	78.08	12.36	100		

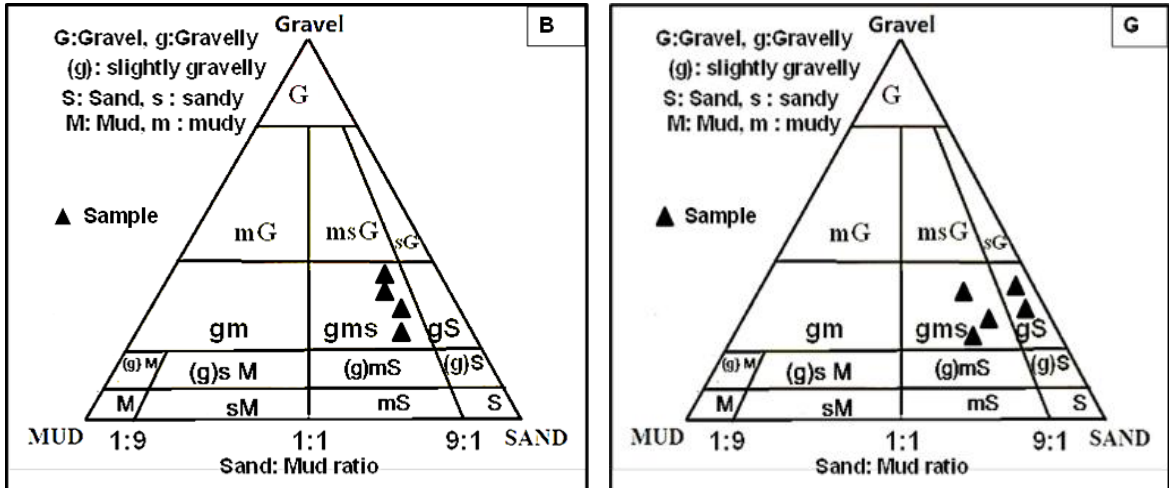


Fig. 4: Ternary diagram of sand, mud and gravel of Mukdadyia Formation in Al-Band (B) and Al-Bajaliah (G) (after Folk, 1974).

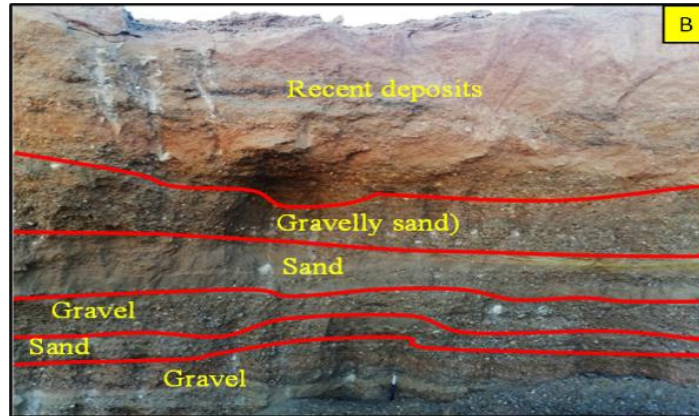


Fig. 5: Sequence of sand and gravelly sand in Al-Band section.



Fig. 6: Sequence of sand and clay in Al-Bajaliah section.

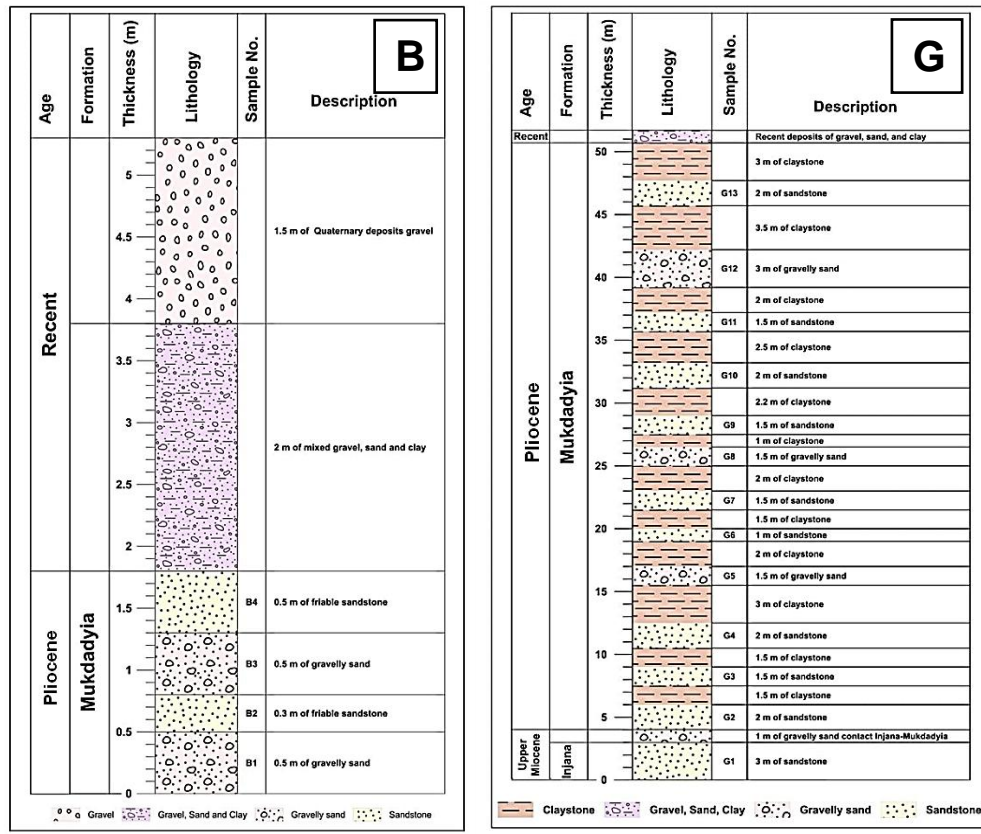


Fig. 7: Stratigraphic section of Mukdadyia Formation in Al-Band (B) and Al-Bajaliah (G).

B. Geochemistry

Major oxides

Al-Band (B) and Al-Bajaliah (G) sandstones have a respectively range of SiO₂ (48.02-56.62 and 49.85-71.79 wt%); Al₂O₃ (3.03-5.11 to 3.78-7.03 wt%), Fe₂O₃ (1.76-2.63 to 2.58-3.43 wt%); rather low K₂O and Na₂O; K₂O (0.86-1.4 to 0.98-1.52 wt%); LOI (15.27-18.46 to 8.44-16.99 wt%); CaO range (18.37-21.94 to 10.72-21.15 wt%); MgO range (0.67-1.15 to 0.82-1.92 wt%); very low SO₃, TiO₂, and P₂O₅ (<1.00 wt%). Silica is the main oxide relative to the content of quartz, rock fragments, ferromagnesian minerals (pyroxene and amphibole). SiO₂ tends to be close to its concentration in the upper continental crust. (Table 2). Other oxides, Al₂O₃, Fe₂O₃, and K₂O, have a proximate concentration in both Al-Band (B) and Bajaliah (G) sections, which also tend to be close to their content in the upper continental crust (Rudnick and Gao, 2003). According to the Sutter and Dutta (1986) diagram, the sediments of Mukdadiya Formation are plotted in the arc field (Fig. 8). According to the Roser and Korsch (1986)

diagram. (Fig. 9), most of the studied samples are situated in the semi-humid climate.

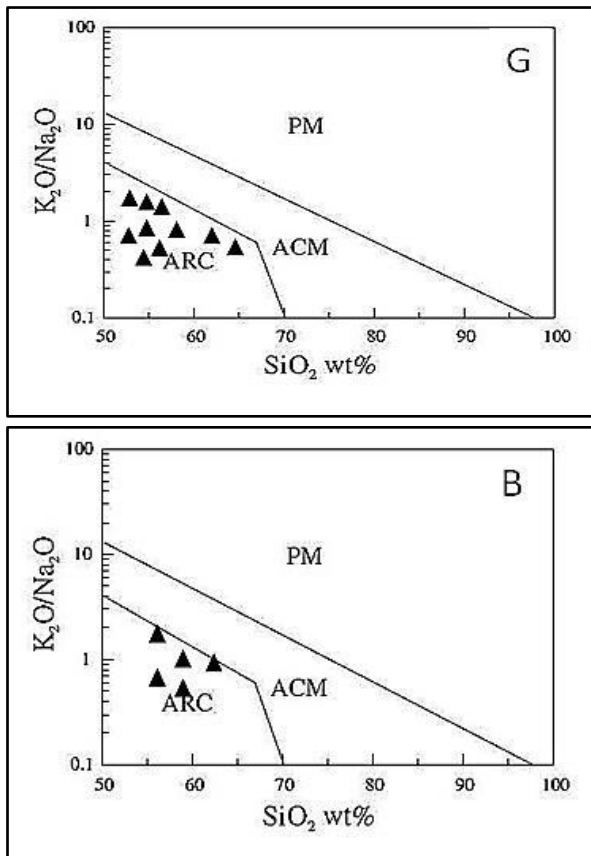


Fig. 8: Tectonic setting for the sandstone Al-Band (B), Al-Bajaliah (G) section after Sutter and Dutta (1986).

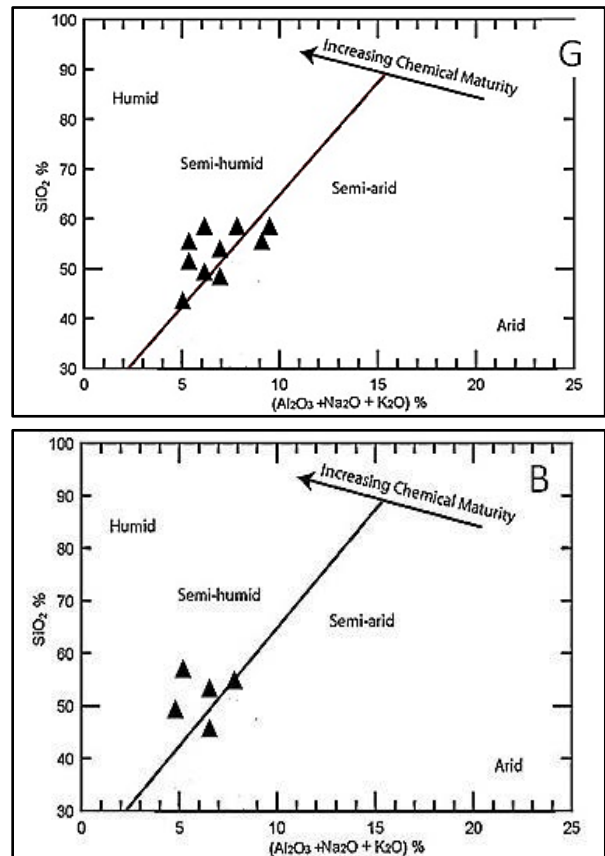


Fig. 9: Paleoclimate for sandstone in Al-Band (B), Al-Bajaliah (G) sections after Roser and Korsch (1986).

Table 2: Major oxides (wt%) in sandstone of Al-Band and Bajaliah sections

LITHOLOGY	SAMPLE	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	TiO ₂	Na ₂ O	CaO	MgO	SO ₃	P ₂ O ₅	L.O.I	TOTAL
sandstone	B1	55.88	4.35	2.15	1.17	0.256	0.54	18.37	0.78	0.08	0.08	15.27	95.91
	B2	56.18	3.39	1.94	0.91	0.196	0.36	19.83	0.67	0.08	0.075	16.29	97.23
	B3	56.62	4.19	2.22	1.18	0.256	0.5	18.44	0.87	0.11	0.089	15.42	96.71
	B4	56.31	3.03	1.76	0.86	0.174	0.33	20.12	0.67	0.1	0.078	16.49	97.41
	B5	48.02	5.11	2.63	1.4	0.33	0.64	21.94	1.15	0.14	0.1	18.46	96.04
	min.	48.02	3.03	1.76	0.86	0.174	0.33	18.37	0.67	0.08	0.075	15.27	95.91
	max.	56.62	5.11	2.63	1.4	0.33	0.64	21.94	1.15	0.14	0.1	18.46	97.41
	average	54.6	4.01	2.14	1.1	0.24	0.47	19.74	0.83	0.1	0.08	16.39	96.66
sandstone	G2	53.53	5.57	3.43	1.37	0.386	0.62	18.33	1.92	0.05	0.102	14.53	99.83
	G4	58.45	5.77	2.95	1.36	0.358	0.62	16.14	1.42	0.06	0.117	12.59	99.83
	G5	65.49	5.37	2.62	1.31	0.305	0.74	12.88	1.11	0.04	0.076	9.92	99.86
	G6	71.79	3.78	2.58	0.98	0.271	0.34	10.72	0.82	0.04	0.062	8.44	99.82
	G7	59.12	5.83	3.15	1.3	0.411	0.83	17.13	1.43	0.05	0.099	13.44	102.7
	G8	55.18	6.39	3.09	1.27	0.446	0.77	17.56	1.16	0.04	0.1	13.84	99.84
	G9	49.85	5.25	2.89	1.25	0.358	0.53	21.15	1.46	0.06	0.087	16.99	99.87
	G10	60.85	5.77	3.39	1.32	0.485	0.81	14.55	1.13	0.04	0.107	11.35	99.80
	G11	63.89	4.77	2.58	0.99	0.289	0.46	14.47	0.89	0.04	0.092	11.3	99.77
	G12	60.62	7.03	3.07	1.52	0.418	1.12	13.84	1.23	0.03	0.095	10.3	99.27
	min.	49.85	3.78	2.58	0.98	0.271	0.34	10.72	0.82	0.03	0.062	8.44	99.27
	max.	71.79	7.03	3.43	1.52	0.485	1.12	21.15	1.92	0.06	0.117	16.99	102.7
		average	59.88	5.55	2.98	1.27	0.37	0.68	15.68	1.26	0.05	0.09	12.27

Total	min.	48.02	3.03	1.76	0.86	0.174	0.33	10.72	0.67	0.03	0.062	8.44	95.91
	max.	71.79	7.03	3.43	1.52	0.485	1.12	21.94	1.92	0.14	0.117	18.46	102.7
	average	57.27	4.875	2.61	1.197	0.315	0.591	17.52	1.075	0.071	0.09	14.15	98.55
UC		66.6	15.4	5.04	2.8	0.64	3.27	3.59	2.48	-	0.15		

Trace elements

The trace elements values are given in (Table .3). High field strength elements (HFSE) like Zr have a range of (29–42 to 36–50 ppm) in the two sections (Al-Band, B and Al-Bajaliah, G) respectively; whereas large ion lithophile elements (LILE) like Ba has a range of (233–420 to 143–575 ppm) respectively; Sr (262–426 to 116–426 ppm) and Rb (23–43 to 23–44 ppm) respectively. Transitional trace elements (TTE) such as Cr, V, and Ni are enriched in the sandstone of both Al-Band (B) and Bajaliah (G): Cr (31–90 to 31–333 ppm), V (28–46 to 28–72 ppm), and Ni (20–38 to 6–103 ppm), respectively. Co, Sc, Cr, Ni, V, and Cu have little variation in the sandstone. The high field strength elements (Th, U, Zr, and Hf) indicate their association with heavy minerals, especially zircon minerals. According to Winchester and Floyd (1977) the diagram of immobile elements (Ti, Zr, Nb, Y) indicate that these elements are concentrated during the late stages of weathering and identifying the andesite as source rock (Fig.10). Moreover, the (Th/Sc vs Zr/Sc) plot according to Taylor and McLennan.(1985) and Condie (1993) shows that sandstone samples are within the field of andesite, which indicates it's derivation from intermediate volcanic rocks (Fig.11).

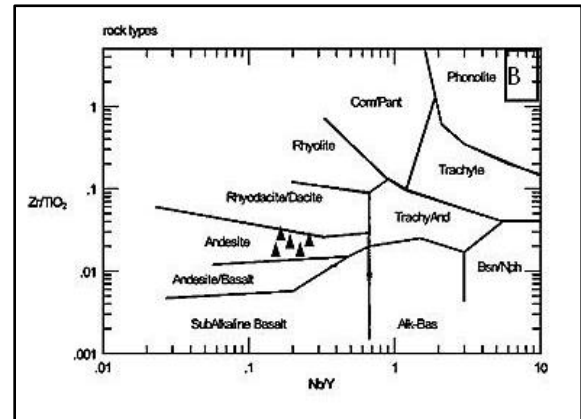


Fig. 10: Discriminant source rock of Al-Band (B) sandstone, Al-Bajaliah (G) Section after Winchester and Floyd (1977)

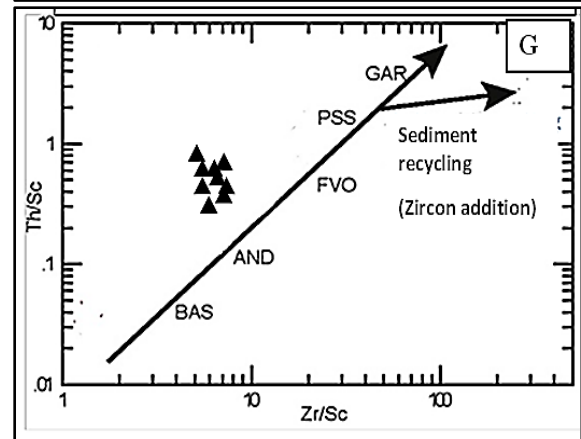
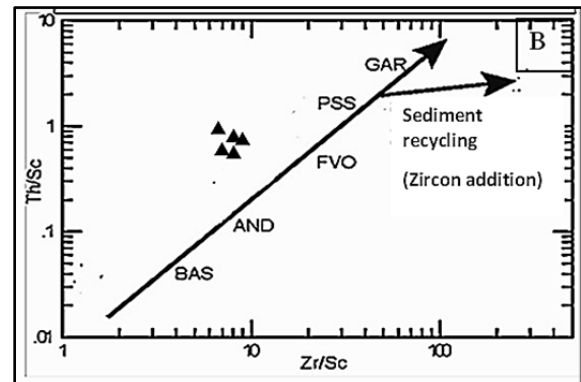


Fig. 11: Discriminant source rock in Al-Band (B); Bajaliah (G) sections after Taylor and McLennan (1985); Condie (1993).

Table 3: Trace elements (ppm) in sandstone of Al-Band and Al-Bajaliah sections

LITHOLOGY	SAMPLE	High Field Strength Elements (HFSE)							Large Ion Lithophile Elements (LILE)		Transition trace elements					
		Zr	Hf	Ta	Nb	Th	U	Y	Rb	Sr	Cr	Ni	Co	V	Sc	Mn
sandstone	B1	35	1.9	0.6	4	3.3	1.2	8.2	36	324	73	24	2	39	3.9	262
	B2	33	1	0.8	4	3.1	1.5	8.3	23	262	47	23	2.6	33	2.8	389
	B3	38	1.3	0.9	5	3.7	1.6	8.9	35	426	68	26	2.6	39	3.7	199
	B4	29	1.7	0.5	3	3.1	1.1	7.3	25	404	31	20	1.2	28	2.7	190
	B5	42	1.2	0.8	5	4.2	1.6	11	43	343	90	38	4.2	46	5.3	356
	min.	29	1	0.5	3	3.1	1.1	7.3	23	262	31	20	1.2	28	2.7	190
max.	42	1.9	0.9	5	4.2	1.6	11	43	426	90	38	4.2	46	5.3	389	
Ave.	35	1.4	0.7	4.2	3.5	1.4	8.7	32.4	351.8	62	26	2.5	37	3.6	279.	
sandstone	G2	36	1.9	0.6	4.5	3.8	0.8	9.3	41	172.9	177	103	8	57	6.9	432
	G4	41	1.2	0.9	5.4	4	0.9	10	44	140.3	103	71	7	48	5.9	370
	G5	43	1.2	0.8	4.6	3.8	1	9.4	40	128.2	56	49	5	42	4.8	324
	G6	38	1	0.8	4.8	3.7	0.9	9.9	30	116.2	79	42	4	43	4.3	209
	G7	47	1.4	0.8	5.2	4.5	1.1	11	40	148.4	163	56	7	53	5.8	363
	G8	45	1.3	0.9	5.2	4.2	1	11	36	144.8	220	44	6	55	5.6	371
	G9	41	1.2	0.9	5.2	3.8	1	11	36	163.6	90	64	7	52	6.1	364
	G10	38	1.1	0.9	4.2	3.3	1	10	26	140.4	87	24	5	45	4.7	321
	G11	50	1.3	0.8	4	4.6	1.2	12	40	179.6	333	6	7	72	6	514
	G12	36	1.9	0.5	4.4	3.8	0.8	9.6	43	160.9	105	6	5	50	5.6	348
	min.	36	1	0.5	4	3.3	0.8	9.3	26	116.2	56	6	4	42	4.3	209
	max.	50	1.9	0.9	5.4	4.6	1.2	12	44	179.6	333	103	8	72	6.9	514
Ave.	42	1.4	1	4.8	4	1	10	37.6	149.5	141	47	6.1	52	5.6	362	
TOT AL	min	29	1	0.5	3	3.1	0.8	7.3	23	116.2	31	6	1.2	28	2.7	190
	max	50	1.9	0.9	5.4	4.6	1.6	12	44	426	333	103	8	72	6.9	514
	Ave.	39	1.4	0.8	4.5	3.8	1.2	9.6	35.4	238.6	106	38	4.5	45	4.8	326
UCC	19 3	5.3	0.9	12	10. 5	2.7	21	82	320	92	47	17. 3	97	14	-	
Shales	16 0	2.8	0.8	11	12	3.7	26	140	300	90	68	19	130	13	850	

REE Geochemistry

The average Σ REE in sandstones of the studied samples is lower than the average recorded in UCC (Turekian and Wedepohl, 1961; Rudnick and Gao, 2003). (Table .4). Both LREE and HREE are higher in the Al-Bajaliah (G) section compared to their average in the Al-Band (B) section. LREE/HREE ratio can be used to know how relative enrichment and depletion are changing in (LREE) and (HREE), and how its importance to identify the kind of source rocks by comparing them to the international standard average. The average of LREE/HREE ratios in both study sections is generally lower than their average in UCC (Turekian and Wedepohl, 1961; Rudnick and Gao, 2003); so LREE are higher than HREE. LREE/HREE ratio tends to increase from Al-Band (B) towards Al-Bajaliah (G). This increase may be related to increasing clay mineral content in sandstone (Cai et al., 2022). The Eu anomaly is an indicator used to detect the provenance of rock and sediments; in plagioclase, Eu^{+2} can frequently replace Ca^{+2} , resulting in a high concentration of

Eu in the plagioclase-bearing rocks. The (Eu/Eu^*) is determined using the equation. $\{\text{Eu} \text{ N}/(\text{SmN}^* \text{GdN})^{0.5}\}$, where (N) stands for chondrite normalization (Taylor and McLennan 1985). According to Murtone et al. (2003), a positive Eu anomaly indicates a delay in plagioclase crystallization. However, a negative Eu anomaly in minerals that crystallize from the magma residue following the separation of plagioclase represents an intermediate stage of magmatic crystallization, as a source rock of Mukdadyia sandstone. Also, a reduction in Eu during weathering and diagenesis may be causing a negative Eu anomaly in sandstone. (Fig.12). Both LREE/HREE ratio averages in sandstone samples of Al-Band (B) (6.3) and Al-Bajalia (G) (7.1) are close to the average in igneous rocks (7.54) and less than that in UCC (9.3) (McLennan et al., 2006) (Table .6). The LaN / LuN ratio indicates the enrichment of LREE/HREE due to the ability of clay associated with the sand fraction to adsorb more LREE than HREE on their surfaces.

Lanthanum-Thorium-Scandium (La-Th-Sc) plot shows that arc-derived sediments and passive margin sediments can be effectively differentiated from each other (Bhatia and Crook, 1986). However, this plot successfully discriminates between the different arc settings. The distinction

between groups is based on an increase in the La/Sc ratio as the sands become more mature (quartz-rich). Mukdadiya sandstone samples are in the field (B), which represents the continental arc (Fig.12).

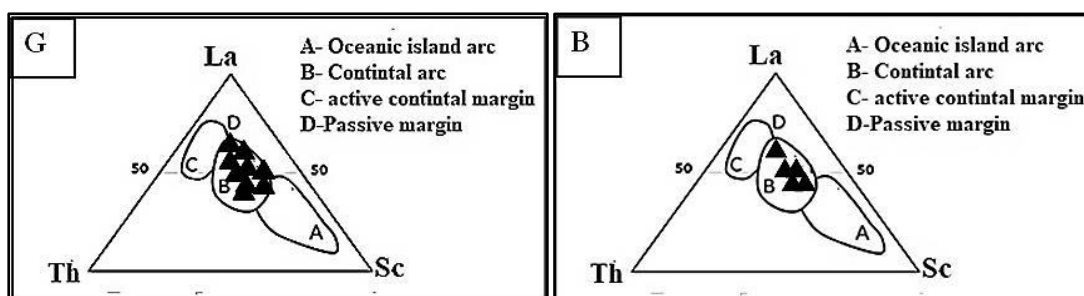


Fig. 12: Lanthanum-Thorium-Scandium plot showing the tectonic setting of Al-Band (B) sediments, Bajaliah (G) sections after Bhatia and Crook (1986).

Table 4: REE (ppm) in sandstone of Al-Band (B) and Al-Bajaliah (G) sections

ITHOLOGY SAMPLE	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	LREE	HREE	Sum REE	LREE/HREE
	sandstone																	
B1	7	23	2.6	8.9	2	0.5	1.87	0.09	3.1	0.1	1.9	0.2	0.77	0.2	49	8.23	57.23	5.954
B2	9	13	3.3	11.5	1.8	0.5	2.22	0.09	1.5	0.09	1.1	0.2	0.76	0.2	39.17	6.16	45.33	6.359
B3	10	16	3.75	13.1	2.4	0.6	2.46	0.09	1.7	0.09	1.2	0.3	0.85	0.2	45.85	6.89	52.74	6.655
B4	10	17	1.97	6.7	1.5	0.4	1.42	0.09	2.9	0.09	1.7	0.2	0.65	0.2	37.57	7.25	44.82	5.182
B5	13	22	4.56	15.6	3	0.7	2.86	0.09	2.1	0.09	1.4	0.3	0.99	0.2	58.86	8.03	66.89	7.33
min	9	13	1.97	6.7	1.5	0.4	1.42	0.09	1.5	0.09	1.1	0.2	0.65	0.2	32.57	5.25	37.82	6.204
max	13	23	4.56	15.6	3	0.7	2.86	0.09	3.1	0.1	1.9	0.3	0.99	0.2	59.86	9.54	69.4	6.275
Av.	10.8	18.2	3.25	11.16	2.14	0.54	2.17	0.09	2.26	0.09	1.46	0.24	0.8	0.2	46.09	7.31	53.4	6.305
sandstone																		
G2	15	27	3.04	10.6	2.2	0.6	2.12	0.2	3.4	0.09	2	0.2	0.87	0.2	58.44	9.08	67.52	6.436
G4	16	24	4.32	15.3	2.6	0.7	2.99	0.09	1.9	0.09	1.3	0.3	0.91	0.2	62.92	7.78	70.7	8.087
G5	11	18	3.66	13	2.2	0.5	2.4	0.09	1.8	0.09	1.2	0.2	0.85	0.2	48.36	6.83	55.19	7.081
G6	11	17	4.05	14.2	2.5	0.6	2.66	0.09	1.8	0.09	1.4	0.3	0.87	0.2	49.35	7.41	56.76	6.66
G7	13	22	4.53	15.9	3	0.7	2.92	0.09	2.3	0.09	1.5	0.3	1.01	0.2	59.13	8.41	67.54	7.031
G8	14	26	4.78	17.3	3.1	0.8	3.01	0.09	2.1	0.09	1.4	0.3	1.05	0.2	65.98	8.24	74.22	8.007
G9	12	19	4.13	14.9	2.6	0.7	2.78	0.09	2	0.09	1.3	0.3	1	0.2	53.33	7.76	61.09	6.872
G10	10	16	3.67	12.7	2.2	0.6	2.35	0.09	1.8	0.09	1.3	0.3	0.95	0.2	45.17	7.08	52.25	6.38
G11	16	28	4.95	18	3.2	0.8	3.03	0.09	2.3	0.09	1.5	0.3	1.15	0.2	70.95	8.66	79.61	8.193
G12	16	32	3.41	12.3	2.5	0.6	2.36	0.2	3.4	0.09	2	0.2	0.85	0.2	66.81	9.3	76.11	7.184
min	10	16	3.04	10.6	2.2	0.5	2.12	0.09	1.8	0.09	1.2	0.2	0.85	0.2	42.34	6.55	48.89	6.464
max	16	32	4.95	18	3.2	0.8	3.03	0.2	3.4	0.09	2	0.3	1.15	0.2	74.95	10.37	85.32	7.228
Av.	13.4	22.9	4.05	14.42	2.61	0.66	2.66	0.11	2.28	0.09	1.49	0.27	0.95	0.2	58.04	8.05	66.09	7.21
TOTAL																		
min	9	13	1.97	6.7	1.5	0.4	1.42	0.09	1.5	0.09	1.1	0.2	0.65	0.2	32.57	5.25	37.82	5.182
max	16	32	4.95	18	3.2	0.8	3.03	0.2	3.4	0.1	2	0.3	1.15	0.2	70.95	9.54	79.61	8.193
Av.	12.27	20.79	3.7	12.97	2.41	0.61	2.44	0.1	2.28	0.09	1.48	0.26	0.89	0.2	52.745	7.733	60.478	6.788
UCC	31	63	7.1	27	4.7	1	4	0.7	3.9	0.8	2.3	0.3	2	0.3	133.8	14.31	148.11	9.35
Shales	92	59	5.6	24	6.4	1	6.4	1	4.6	1.2	2.5	0.2	2.6	0.7	188	19.2	207.2	9.792

Rare Earth Elements Patterns and origin of Mukdadiya sandstone

The concentration of REE is normalized to Chondrites - CI type rocks (Barrat et al.,2012) (Table 5). The normalized patterns of REE in the

sandstone of Al-Bajaliah (G) and Al-Band (B) reveal a trend of LREE enrichment and HREE depletion. The enrichment and depletion of REE depend on the REE content in the source area. Since particle grain size has an important role in REE enrichment, mud can attract REE and adsorb

on clay surfaces. The patterns of the REE in sandstone were compared to those in sandstone of the upper continental crust (UCC), average shale, and basalt of the mid-oceanic ridge (White, 2001) (Fig. 13). REE patterns in Sandstone samples are between UCC (felsic) and MORB (basic) patterns. Moreover, the REE patterns were compared with their patterns in acidic, intermediate, and basic igneous rocks, including granite, andesite, basalt, and Gabbro (Fig. 14). The behavior of REE in studied samples refers to the occurrence between intermediate (andesite) and basic rock (basalt). Resulting from the continental and oceanic collisions between the Arabian and Iranian plates (Numan, 1997). The result indicates subduction

and the rise of basic magma in combination with magmatic differentiation, indicating the presence of ophiolite complexes in northeastern Iraq, which may be a major source of sediments (Al-Juboury et al., 2009; Al-Sultan,2014). These results are consistent with the Injana Formation (underlying) of basic to intermediate source (Al- Najjari, 2019; Al-Maadhidi et al.,2025). The current study suggests that the tectonic environment was a continental arc, as well as emphasizing the fact that the intermediate to basic origin is the main source of Mukdadyia sandstone according to the elemental geochemical ratios (Table 6) that have been compared with the international standard (Cullers,2000; McLennan et al., 2006).

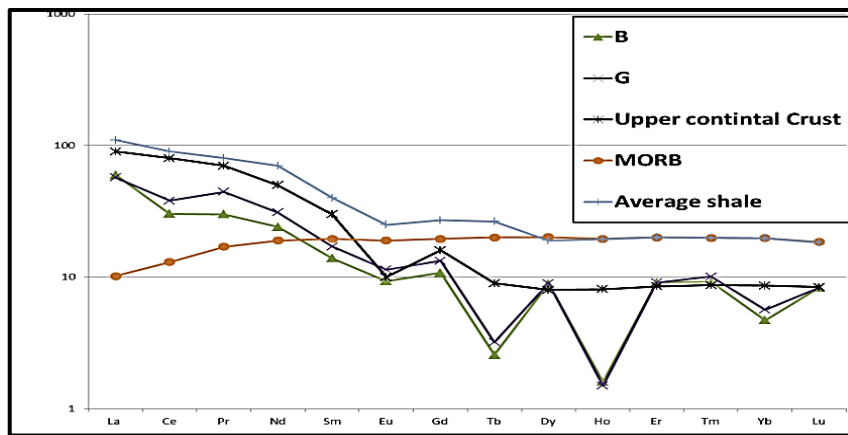


Fig. 13: CI- Normalized REE patterns for sandstone Al-Band (B) and Al-Bajaliah (G), in comparison with UCC, MORB, and average shale (White, 2001)

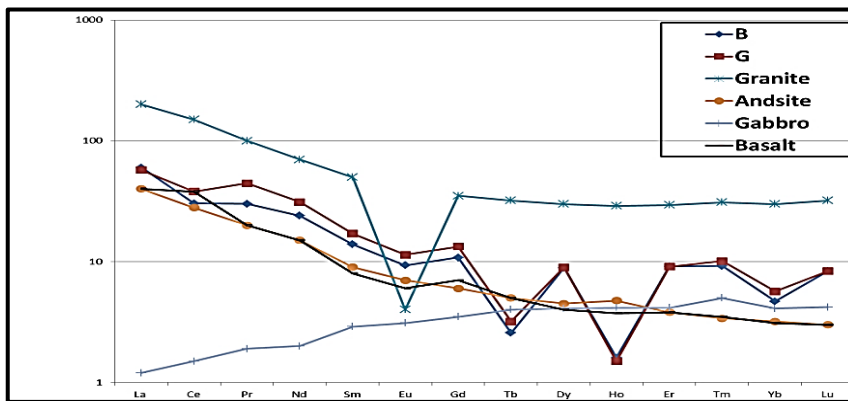


Fig 14: CI-Normalized REE patterns for Sandstone and siltstone samples: Al-Band (B) and Al-Bajaliah (G); in comparison with Granite, Andesite, Gabbro, and Basalt (White, 2001)

Table 5: REE (ppm) in chondrite- CI(REE) and REE(N) in sandstones of Al-Band (B) and Al-Bajaliah (G) sections.

Chondrite C1	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb
Barrat <i>et al.</i> 2012	0.235	0.6	0.091	0.464	0.153	0.058	0.2	0.035
Sample	La (N)	Ce (N)	Pr (N)	Nd (N)	Sm (N)	Eu (N)	Gd (N)	Tb (N)
sandstone	B1	51.0	38.33	28.5	19.18	13.07	8.621	2.571
	B2	38.298	21.667	37.033	24.784	11.765	8.621	11.1
	B3	42.553	26.667	41.209	28.233	15.686	10.345	12.3
	B4	42.553	28.333	21.648	14.44	9.804	6.897	7.1
	B5	55.319	36.667	21.648	33.621	19.608	12.069	14.3

	min	38.298	21.667	21.648	14.44	9.804	6.897	7.1	2.571	
	max	55.319	38.333	41.209	33.621	19.608	12.069	14.3	2.571	
	Av.	45.96	30.33	30.02	24.05	13.99	9.31	10.83	2.57	
sandstone	G2	63.83	45	33.407	22.845	14.379	10.345	10.6	5.714	
	G4	68.085	40	47.473	32.974	16.993	12.069	14.95	2.571	
	G5	46.809	30	40.22	28.017	14.379	8.621	12	2.571	
	G6	46.809	28.333	44.505	30.603	16.34	10.345	13.3	2.571	
	G7	55.319	36.667	49.78	34.267	19.608	12.069	14.6	2.571	
	G8	59.574	43.333	52.527	37.284	20.261	13.793	15.05	2.571	
	G9	51.064	31.667	45.385	32.112	16.993	12.069	13.9	2.571	
	G10	42.553	26.667	40.33	27.371	14.379	10.345	11.75	2.571	
	G11	68.085	46.667	54.396	38.793	20.915	13.793	15.15	2.571	
	G12	68.085	53.333	37.473	26.509	16.34	10.345	11.8	5.714	
		min	42.553	26.667	33.407	22.845	14.379	8.621	10.6	2.571
		max	68.085	53.333	54.396	38.793	20.915	13.793	15.15	5.714
	Av.	57.02	38.17	44.55	31.08	17.06	11.38	13.31	3.2	
TOTAL	Min	38.298	21.667	21.648	14.44	9.804	6.897	7.1	2.571	
	Max	68.085	53.333	54.396	38.793	20.915	13.793	15.15	5.714	
	Av.	53.333	35.556	39.707	28.736	16.035	10.69	12.48	2.9901	

Chondrite C1		Dy	Ho	Er	Tm	Yb	Lu			
Barrat <i>et al.</i> 2012		0.254	0.0566	0.16	0.026	0.168	0.024	Eu*	Eu/Eu*	La(N)/Lu(N)
	Sample	Dy (N)	Ho (N)	Er (N)	Tm (N)	Yb (N)	Lu (N)			
sandstone	B1	12.205	1.767	11.875	7.692	4.583	8.333	0.78	0.64	6.13
	B2	5.906	1.59	6.875	7.692	4.524	8.333	0.75	0.67	4.6
	B3	6.693	1.59	7.5	11.54	5.06	8.333	0.74	0.811	5.11
	B4	11.417	1.59	10.625	7.692	3.869	8.333	0.83	0.482	5.11
	B5	8.268	1.59	8.75	11.54	5.893	8.333	0.72	0.972	6.64
	min	5.906	1.59	6.875	7.692	3.869	8.333	0.72	0.482	4.6
	max	12.205	1.767	11.875	11.54	5.893	8.333	0.83	0.972	6.64
	Av.	8.9	1.63	9.13	9.23	4.79	8.33	0.76	0.71	5.52
sandstone	G2	13.386	1.59	12.5	7.692	5.179	8.333	0.84	0.71	7.66
	G4	7.48	1.59	8.125	11.54	5.417	8.333	0.76	0.92	8.17
	G5	7.087	1.59	7.5	7.692	5.06	8.333	0.66	0.76	5.62
	G6	7.087	1.59	8.75	11.54	5.179	8.333	0.7	0.86	5.62
	G7	9.055	1.59	9.375	11.54	6.012	8.333	0.71	0.99	6.64
	G8	8.268	1.59	8.75	11.54	6.25	8.333	0.79	1.01	7.15
	G9	7.874	1.59	8.125	11.54	5.952	8.333	0.79	0.89	6.13
	G10	7.087	1.59	8.125	11.54	5.655	8.333	0.8	0.75	5.11
	G11	9.055	1.59	9.375	11.54	6.845	8.333	0.77	1.04	8.17
	G12	13.386	1.59	12.5	7.692	5.06	8.333	0.75	0.8	8.17
	min	7.087	1.59	7.5	7.692	5.06	8.333	0.66	0.71	5.11
	max	13.386	1.59	12.5	11.54	6.845	8.333	0.84	1.04	8.17
	Av.	8.98	1.59	9.31	10.38	5.66	8.33	0.76	0.87	6.85
TOTAL	Min	5.906	1.59	6.875	7.692	3.869	8.333	0.66	0.482	4.6
	Max	13.386	1.59	12.5	11.54	6.845	8.333	0.84	1.04	8.17
	Av.	8.9503	1.6018	9.25	10	5.369	8.333	0.75	0.82	6.4

Table 6: Comparison of REE average in international shale, sandstone, igneous rock, upper continental crust and current study (Cullers, 2000), (McLennan et al., 2006).

Elements		Eu/Eu*	LREE	HREE	REE	LREE/HREE
Turckain & Wedepohl, 1961	Shales	0.46	188	19.2	207.2	9.79
Rudnick &	Sandstone	0.5	179.4	30.3	209.7	5.92

Gao 2003	Igneous rock	0.7	133.4	17.7	151.1	7.54
	UCC	0.72	133.8	14.34	148.1	9.33
Current study	B	0.71	46.09	7.31	53	6.3
	G	0.76	56.91	7.9	61	7.1

5. Conclusion

1. The diagrams of $\text{SiO}_2 + \text{Al}_2\text{O}_3$ and $\text{K}_2\text{O} + \text{Na}_2\text{O}$ show a semi-arid to arid climate condition during the deposition of Mukdadyia Formation.
2. The plots of Nb/Y & Zr/TiO_2 , and the ratios of Th/Sc and Zr/Sc reveals andesitic rock as a source of Mukdadyia sandstone.
3. The REE normalized patterns in sandstone show an enrichment in LREE and depletion in HREE in both studied sections.
4. The negative Eu anomaly is slightly closer between basalt and andesite, resulting from the continental and oceanic collisions between the Arabian and Iranian plates. This is supported by the discrimination diagram (La-Th-Sc), representing the continental island arc.
5. LaN/LuN ratio increases with the increase of the clay content, as associated with sand in both sections due to the ability of the clay to adsorb the LREE on their surfaces.
6. REE patterns in sandstone show similarity to patterns of intermediate (andesite) and, to a lesser extent, to their patterns in basic (basalt) igneous rocks.

6. References

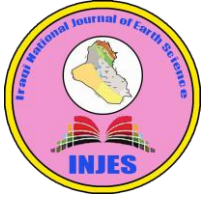
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جيوكيميائية وأصل الصخور الرملية لتكوين مقدادية، شرقي العراق

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الملخص

تمت دراسة تكوين مقدادية في شرقي العراق من الناحية الجيوكيميائية، واختير لهذا الغرض مقطعان سطحان في منطقتي البند والبلجبة. حلت 15 عينة من الصخور الرملية باستخدام تقنية الأشعة السينية المتطورة وجهاز قياس الطيف الكتلي للبلازما المقترن حثياً لتحديد محتواها من الاكاسيد الرئيسية (Fe_2O_3 , SiO_2 , La , Ce , Pr , Cr , Ni , Co , V , Sc , Zr , Hf , Ta , Nb , Th , U , Y , Rb , Sr) والارضية النادرة (Nd , Pm , Sm , Eu , Gd , Tb , Dy , Ho , Er , Tm , Yb , Lu). أشارت مخططات SiO_2 مقابل $(Al_2O_3+K_2O+Na_2O)$ الى ان الصخور الرملية لتكوين مقدادية قد ترسبت تحت ظروف مناخ جاف الى شبه جاف، وأكدت تصاحب كل من Cr , Ni , Co , V , Sc ذات الاصل الناري المتوسط الى هذه الرواسب. ازاد محتوى الرمال من عناصر Zr , Hf , Th , U , Sr بسبب مقاومة هذه العناصر للتجوية الكيماوية. اشارت مخططات نسب Nb/Y , Zr/TiO_2 الى الاصل الناري المتوسط للصخور الرملية لتكوين مقدادية، بينما اشارت نسب العناصر الارضية النادرة الخفيفة/الثقيلة LaN/LuN و Eu/Eu^* الى الاعتناء بالعناصر الارضية الخفيفة التي تتركز في الاجزاء الطينية الناعمة مع زيادة المحتوى الطيني. وبنيت مخططات $La-Th-Sc$ ان الصخور الرملية تقع في حقل صخور الاقواس البركانية القارية. كما اشارت انماط العناصر الارضية النادرة الى مساهمة كل من الصخور المتوسطة (انديسايت) والقاعدية (البازلت) في الاصول المتوقعة لرمال تكوين مقدادية.

الكلمات المفتاحية:

الصخور الرملية ، انديسايت، العناصر الارضية النادرة، جيوكيميائية، التجوية الكيماوية.

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