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Heavy Minerals Study of Sandstone from the Late Miocene-Early Pliocene Mukdadiya Formation; Kirkuk, Iraq: Implications for Provenance

Abbas R. Ali

Department of Applied Geology, College of Science, University of Kirkuk, Kirkuk, Iraq

Correspondence: abbaskervanci@uokirkuk.edu.iq

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Abstract

Mukdadiya Formation (Late Miocene-Pliocene) exposed in the northeastern limb of Baba anticline fold in Kirkuk structure. The selected section was located in Shoraw area, northeastern Kirkuk city, Iraq. Twenty sandstone samples were collected to study heavy minerals. The study indicates that opaque and epidote group minerals forming the main heavy minerals, followed by amphibole, pyroxene, garnet and chlorite. According to heavy minerals assemblage, the source rocks are interpreted to be composed essentially of sedimentary followed by igneous and metamorphic rocks and the high contents of unstable and metastable minerals confirm their direct derivation from the adjacent primary source. Ultra-stable and metastable heavy minerals relationship indicated that the sandstone of the Mukdadiya Formation is immature and moderate stability and showed that these minerals couldn't be transported for very long distances close to the source area and not represents polycyclic grain. MF-MT-GM Ternary diagram showed that the studied samples fall within the field of active continental margins which is characterized by a relatively high percentage of minerals (MF>GM) derived from mafic magmatic rocks.

Keywords: Heavy mineral; Mukdadiya Formation; Sandstone; Provenance; Kirkuk

1. Introduction

Minerals with a density greater than 2.86 g/cm³ in siliciclastic sediments are called heavy minerals (Mange and Maurer, 1992). They usually occur as accessory minerals in rocks. These minerals are useful indicators of sediment source rocks (provenance) because different types of source rocks yield different suites of heavy minerals (Van Andel, 1959; Hubert, 1962; Morton, 1985). Morton (2003) and Morton and Hallsworth (1994) illustrated that heavy mineral analysis is one of the most powerful and widely used methods in determining sediment provenance because of its sensitivity to source rock lithology. They are deposited and sorted according to differences in size, shape and density (Haredy, 2008). Heavy minerals are derived from a variety of igneous, metamorphic, and sedimentary rocks, these minerals not only occur in sedimentary rocks, but are also found in different types of unconsolidated sediments. Heavy minerals are present in their source rocks either as primary (e.g. amphiboles, pyroxenes, micas) or accessory (e.g. zircon, apatite and tourmaline) mineral constituents (Mange and Maurer, 1992). Depends on the relative chemical stability of heavy minerals, Folk (1974) classified the heavy minerals into four groups; these include the unstable, the semi-stable, metastable and ultra-stable groups. The main objective of the current study is to shed light on the heavy mineral

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assemblage from twenty selected sandstone samples of the Mukdadiya Formation, and it discusses the provenance and distributions of these minerals.

2. Geological Setting

The study area lies in the unstable shelf within the Foothill zone in Shoraw region (Jassim, et al. 1984), which represents the northeastern limb of Baba anticline fold, within longitude ($35^{\circ} 48' 38''$ - $35^{\circ} 32' 34''$) and the latitude ($44^{\circ} 32' 39''$ - $44^{\circ} 23' 12''$), about 10 km. northeastern of the city center on the right side of Kirkuk – Erbil road (Fig. 1). The Mukdadiya Formation (Late Miocene – Early Pliocene) was previously named in Iran as Lower Bakhtiari by Busk and Mayo (1918) and was later changed in Iraq to the Mukdadiya Formation (Jassim et al. 1984; Al-Rawi et al. 1992). The Mukdadiya Formation crops out in the east and northeast (Khalkhalan Dagh Mountains). It consists of sand, silt, clay, sandstone and gravel with increasing its diameter upwardly to form conglomerate. Mostly, it is widespread along the synclinal limbs and the parts around the basin. Pebbly sandstone is unconformable lower boundary with the Injana Formation by angular contact (Buday, 1980). The clastic sequence of the Mukdadiya Formation is widely distributed in the foothill and the Mesopotamian plain zones. Due to its thickness (Maximum 2050 m) and its stratigraphic position, it plays an important role in the geology of the Middle East (Ali and Khoshaba, 1981). The formation was studied stratigraphically and sedimentologically by many authors (Van Bellen et al. 1959; Yacoub et al. 1990; Jassim et al. 1984; Al-Rawi et al. 1992). All those authors suggested that the formation is of continental to sub-continental fluvial environment. Moreover, Al-Addool (1982) indicated that the formation was deposited in braided and meandering channels in northern Iraq. Otherwise, the formation sediments were described as a fluvio-lacustrine by Jassim and Goff (2006). The recent geological studies indicate that the clastics of the formation are of fluvial environment (Al- Khalidi, and Al-Shimmari, 2015). The Mukdadiya Formation is underlain by the Injana formation (Late Miocene), and composed principally of fining upward cycles of clastics, mainly sandstones, pebbly sandstones, grey mudstones and siltstones. Moreover, few gravelly sandstone units were observed (Basi, 2012). Its thickness is (supposed) to be 1400-3500 m. It is thought to be deposited in a fluvial environment in a rapidly subsiding foredeep basin. The lower contact of the Mukdadiya Formation can be detected on the first appearance of pebbles in the sandstone units (Van Bellen et al., 1959). This bed separates between Miocene and Pliocene ages. The upper contact of the Mukdadiya Formation with the Bai Hassan formation can be detected on the first appearance of conglomerate unit (Al-Naqib, 1960).

3. Materials and Methods

A total of twenty samples were collected from selected sites of the Mukdadiya Formation at Shoraw area, northeastern Kirkuk City, Iraq. Each sample represents the sandstone units of each sedimentary cycle, all the samples were subsequently air dried and then were segregated sand fraction of 250-63 micrometer from the other sizes and cement materials. According to Carver (1971) and Mange and Maurer (1992) heavy liquid (bromoform) with a specific gravity of 2.89 used to separate the heavy fraction from light ones. Each heavy fraction samples were washed on filter paper with acetone, dried out and part of them mounted on glass slides with canada balsam (RI= 1.52) for heavy minerals study by binocular polarized microscope. The Preparation and separation heavy minerals were achieved at Department of Applied Geology, College of Science, University of Kirkuk. The quantitative analyses (point counting) were performed to using the Ribbon counting technique, which is the most popular method for heavy minerals (Mange and Maurer, 1992). The counting results were then converted to numeric percentage for heavy mineral fractions as listed in Table 1. The assemblages of heavy minerals have been recognized and divided into transparent and opaque minerals (Deer et al. 1992; Mange and Maurer, 1992) (Tables 1 and 2).

Fig.1. Geological map of northern Iraq showing the location of the studied area. Modified from the Geological Map of Iraq (1986), in Al-Juboury and Al Al-Miamary (2009)

4. Results and Discussion

4.1. Petrography of Heavy Minerals

The heavy minerals assemblage is characterized by abundant opaque minerals, which represent 30% of the total heavy mineral contents. Unstable minerals including amphibole, pyroxene and glaucophane, represent more than 28% of the transparent heavy minerals and to a lesser extent epidote. Whereas garnet and chlorite are present in most of the samples. Zircon, tourmaline, rutile and staurolite are present in small or traces amount in some samples. Table (1) illustrates the relative abundances of the opaque and main transparent heavy minerals in the studied samples.

4.1.1. Opaque minerals

Opaque minerals have the highest percentage of heavy minerals and are recorded in all the studied samples, with ranges of 23.45 – 37.12 % and an average of 29.84 % (Table 1). The shapes of the identified minerals are dominantly sub-rounded to sub-angular (Fig. 2D). The high specific of opaque minerals relates with the iron content (Folk, 1974). The existence of opaque minerals in the studied samples indicates acidic and basic igneous rocks as well as metamorphic rocks.

4.1.2. Unstable minerals

- Amphibole

Amphiboles constitute an extremely complex group of minerals that form in a variety of igneous and metamorphic rocks (Pettijohn et al. 1973). Ehrmann and Polozek (1999) illustrated that amphibole indicating a predominantly igneous source rock. They are the most abundant group in the studied transparent unstable heavy minerals, and consists mainly of hornblende with subordinate tremolite-actinolite and rare glaucophane. The percentage of amphibole group mineral ranges between 6.45-20.56% with an average of 14.36 % (Table 2). The hornblende is characterized by light green to brownish green and brown colors with clear pleochroism from green to pale green (Figs. 2A and B). Tremolite-actinolite is characterized by colorless to light grey without pleochroism, with low extinction angle.

- Pyroxene

Pyroxene grains are the second major constitute of the unstable minerals in the Mukdadiya Formation in the studied sections. The percentage of pyroxene ranges from 4.34 – 22.41 % with an average of 14.16 % (Table 2). Pyroxene is the most important group of ferromagnesian rock forming minerals. They occur in almost every type of igneous and metamorphic rocks, and crystallized under a range of different conditions (Deer et al. 1992; Mange and Morton, 2007). It appears in the source rocks of basic and ultrabasic igneous rocks (Krumbein and Sloss, 1963; Pettijohn, 1975; Tucker, 1991). Pyroxene is colorless to light yellowish green in color with no or weak pleochroism, partially to weakly corroded and parallel extinction. Pyroxene grains show a diagenetic feature like saw-tooth (Fig. 2C) because of the solutions and they also show weathering features and pitting. Pyroxene and amphiboles tend to be unstable under weathering circumstances (Turcker, 1981).

Table 1. Total heavy minerals, opaque and non-opaque minerals content in the sandstone samples of the Mukdadiya Formation

Sample	Total heavy minerals (%)	Opaque minerals (%)	Non - opaque minerals (%)
B1	1.45	32.55	67.45
B2	1.12	37.12	62.88
B3	3.24	30.45	69.55
B4	3.41	28.99	71.01
B5	10.15	35.14	64.86
B6	0.95	27.35	72.65
B7	0.42	26.12	73.88
B8	16.32	34.61	65.39
B9	0.88	25.14	74.86
B10	0.87	23.45	76.55
B11	3.84	25.14	74.86
B12	4.59	31.12	68.88
B13	3.11	30.55	69.45
B14	0.92	28.11	71.89
B15	2.38	30.14	69.86
B16	2.02	30.25	69.75
B17	0.97	29.17	70.83
B18	1.87	27.19	72.81
B19	1.83	33.28	66.72
B20	1.08	31.02	68.98
Average	3.07	29.84	70.16
Minimum	0.42	23.45	62.88
Maximum	16.32	37.12	76.55

4.1.3. Metastable minerals

- Epidote

The epidote is the most abundant mineral in the studied samples, it is generally found in the igneous rocks, occur exist mostly in rocks from the greenschist, epidote-amphibolite facies (Asiedu et al. 2000). The percentage of epidote ranges from 16.42 – 31.83% with an average of 24.11% (Table 2). Generally, epidote grains appear as angular to sub rounded in shape and appear as yellowish green to pale brown (Fig. 2E). Epidote is dominant in the low to medium grade metamorphic rocks (Mange and Maurer, 1992).

Table 2. Average abundance of heavy mineral (%) in the sandstone samples of the Mukdadiya Formation

Sample	Unstable Minerals		Metastable Minerals			Flaky Minerals		Ultra-stable Minerals		
	Amphibole	Pyroxene	Epidote	Garnet	Staurolite	Chlorite	Biotite	Tourmaline	Rutile	Zircon
B1	15.55	16.54	18.61	4.12	0.72	7.89	0.98	1.02	0.14	1.88
B2	13.01	13.73	18.62	6.25	0.24	6.78	0.54	2.24	0.22	1.25
B3	12.92	17.88	23.44	3.21	0	8.47	0.98	1.78	0.12	0.75
B4	7.23	18.95	19.48	4.88	0	14.66	2.77	1.59	0	1.45
B5	13.54	12.19	26.77	7.96	0	2.28	0.39	1.41	0	0.32
B6	14.35	14.88	20.83	17.32	0	3.12	0.42	0.75	0	0.98
B7	12.35	21.7	26.09	6.35	0.44	4.52	0.55	0.57	0.54	0.77
B8	15.9	6.53	27.77	4.88	0.12	7.98	0	0.89	0.87	0.45
B9	16.79	22.41	22.14	4.02	0	5.66	0.87	1.21	0.54	1.22
B10	6.45	18.65	29.14	4.11	0	15.32	0	0.44	1.21	1.23
B11	18.68	18.38	29.65	4.01	0.32	0.98	0	1.22	0.61	1.01
B12	17.92	4.34	28.87	7.52	0	6.78	0	1.18	0.75	1.52
B13	15.91	7.4	22.25	7.96	0	10.89	2.31	1.17	0.42	1.14
B14	16.98	17.99	24.51	6.32	0.21	1.87	0.44	0.55	0.51	2.51
B15	13.33	13.47	20.36	15.33	0.23	0.55	1.87	1.05	0.65	3.02
B16	12.05	8.35	28.49	5.15	0	9.87	2.46	1.44	0.7	1.24
B17	12.77	4.81	31.83	3.25	0.35	10.24	2.19	2.03	0.12	3.24
B18	12.89	13.71	22.49	7.66	0.6	9.21	1.25	2.01	0.12	2.87
B19	17.97	18.63	16.42	8.55	0	1.31	0.82	1.52	0.52	0.98
B20	20.56	12.61	24.47	6.77	0.11	1.25	0.57	0.57	0.65	1.42
Average	14.36	14.16	24.11	6.78	0.17	6.48	0.97	1.23	0.43	1.46
Minimum	6.45	4.34	16.42	3.21	0	0.55	0	0.44	0	0.32
Maximum	20.56	22.41	31.83	17.32	0.72	15.32	2.77	2.24	1.21	3.24

- Garnet

The percentage of garnet ranges from 3.21 - 17.32 % with an average of 6.78 % (Table 2). It is an isotropic and has high relief shape, mostly colorless and rarely brownish. Most of the crystals are angular and hexagonal (Fig. 2F). Garnet is a relatively stable mineral under both weathering and burial diagenetic conditions (Morton and Hallsworth, 1999). It is especially characteristic of metamorphic rocks (Kerr, 1959; Mason and Berry, 1968).

Fig. 2. Types of heavy minerals in sandstone samples of the Mukdadiya Formation include:

- A. Green color, subhedral actinolite (Amphibole group), sample number B9.
- B. Dark green color, subhedral hornblende (Amphibole group), sample number B20.
- C. Greenish yellow, anhedral pyroxene (cockscomb texture), sample number B9.
- D. Opaque grain (iron oxide), sample number B2.
- E. High relief, brown color epidote, sample number B20.
- F. Colorless, anhedral garnet grain, sample number B6.
- G. High relief, yellowish color staurolite, sample number B18.
- H. Green color, flaky form chlorite, sample number B4.
- I. Brown pleochroic flaky biotite, sample number B16.
- J. High relief assemblage of zircon grains, sample number B15
- K. Brownish color, subhedral tourmaline, sample number B18.
- L. High relief, deep yellow red rutile, sample number B10.

- Staurolite

Staurolite is observed in sporadically (few samples, scarce in others). It is generally found in metamorphic rocks as a result of regional metamorphism in intermediate to high grade (Elsner, 2010).

The percentage of staurolite ranges from 0-0.72 % with an average of 0.17 % (Table 2 and Fig. 2G). It is a regional metamorphic phase of intermediate to high grade. Whereas (Mason and Berry, 1968) illustrated that staurolite is also one of the index minerals that are used to estimate the temperature, depth, and pressure at which a rock undergoes metamorphism.

4.1.4. Flaky minerals

- Chlorite

Chlorite is mostly secondary in origin formed from alteration of ferromagnesian silicate minerals. Also, chlorite is derived from metamorphic rocks (Hibbard, 2002). The percentage of chlorite in the studied samples ranges (0.55 – 15.32 %) with the average of 6.48 % (Table 2). It is mostly green in color and varies from rounded to sub rounded. Some grains show fractures and inclusion of opaque minerals (Fig. 2H).

- Biotite

Biotite is observed in some studied samples with small relatively percentage (0.0 – 2.77 %) and an average ratio (0.97 %) (Table 2). This mineral occurs as angular to sub-angular at the studied samples, it appears as brown to yellow flakes, which are strongly pleochroic, the cleavage is distinct (Fig. 2I).

4.1.5. Ultra-stable minerals

- Zircon

Zircon is observed in most of the studied samples with relatively low content ranging between 0.32 – 3.24 % with average ratio (1.46 %) (Table 2). It has a light green color with euhedral shape and prismatic habit with very high relief without cleavage (Fig. 2J). Zircon is widely distributed in granites and syenites (Folk, 1974; Pettijohn, 1975). Zircon has a tetragonal symmetry but its internal crystal structure may often be damaged by bombardment from the decay of radioactive elements present in small amounts in many zircons. It is resistant to destruction during erosion and deposition. (Klein, 2002; Al-Malabeh et al., 2017). Zircon is a good indication for the source rock; thus, its euhedral shape is indications to the acidic igneous rock and the rounded shape is indication for the high grad metamorphic rocks (Speer, 1982).

- Tourmaline

Tourmaline content fluctuates from 0.44 – 2.24 % with an average of 1.23 % (Table 2). It has moderately relief and distinct pleochroism. It appears as tabular or irregular shape (Fig. 2K). Elawi (2005) illustrated that the presence of tourmaline in different colors and shapes are associated with the none-opaque minerals especially rutile. Tourmaline derived from felsic igneous rocks especially granite, metamorphic rocks. (Petijohn et al., 1972 and Tucker, 1985). But the presence of tourmaline and zircon in trace amounts may give an indication for the weak role of acidic rocks in the source area (Khorsheed and Ali, 2015).

- Rutile

Rutile formed predominantly metamorphic rocks in addition granites, granite pegmatite and limestone and dolomite (Meinhold, 2010). Rutile is red and deep yellow red in color, high in relief and sub rounded to rounded crystal shape (Fig. 2L). Rutile ranges (0.0 – 1.21 %) and average of 0.43 % (Table 2). Rutile is widely distributed as accessory mineral in metamorphic and felsic igneous rocks (Tucker, 1991; Boggs, 1995).

4.2. Provenance of the Sediments

The most common association of heavy minerals in the studied sediments is the epidote, amphibole and pyroxene, which represent more than 50% of the non-opaque heavy minerals, which indicates that these minerals couldn't have been transported for great distance and didn't represents polycyclic grains. The relationship between ultra-stable minerals (ZTR, zircon, tourmaline and rutile) and metastable minerals (garnet and staurolite) in the Mukdadiya Formation indicates that the Mukdadiya sandstone sediment immaturity (Fig. 3A) (Pettijohn, 1975). According to the Kasper et al., (2008), the sandstone samples are plotted near the moderately stable of ternary as shown in Fig. 3B which indicating moderate stability of sediment because of the high percentage of opaque minerals with the participation of amphibole and epidote, this means that these minerals could not be transported for very long distances and were accumulated close to the source area and not represents polycyclic grain (Prothero and Schwab, 2014). The relationship between tectonic setting and composition of sediment and their implication as tectonic environments indicators was clarified by Pettijohn, et al., (1972). The heavy mineral assemblages of the sediments may be used as criterion for differentiation of the intra-oceanic, island arc and deep marginal sea region sediments. The assemblage of heavy minerals can distinguish between some tectonic settings (Nechaev and Isphording, 1993). Plotting of percentage of heavy minerals on a right angle MF-MT-GM ternary diagram, thus the common minerals of mafic magmatic, common minerals of basic metamorphic and accessory minerals of granites and metamorphic were represented by (MF), (MT) and (GM) respectively. In particular, MT (at the right angle corner of the diagram) is less certain in distinguishing between sediments of different tectonic settings than the other two components (Mohamed and Dar, 2005). The analytical data as percentage plotted in MF-MT-GM ternary diagram, shows that the heavy mineral assemblage in the studied samples are clearly reflect the immaturity sandstone of the Mukdadiya Formation because they are located in the field of the active continental margin where ($MF > GM$) in the samples (Fig. 4 and Table 3).

Table 3. Heavy mineral data of sandstone sediments of the Mukdadiya Formation

Sample No.	MF%	MT%	GM%
B1	32.09	38.28	3.62
B2	26.74	37.88	3.73
B3	30.8	39.57	2.53
B4	26.18	31.59	3.04
B5	25.73	48.27	1.73
B6	29.23	52.5	1.73
B7	34.05	44.79	1.78
B8	22.43	48.55	1.46
B9	39.2	42.95	2.43
B10	25.1	39.7	1.67
B11	37.06	52.34	2.55
B12	22.26	54.31	2.7
B13	23.31	46.12	2.31
B14	34.97	47.81	3.27
B15	26.8	49.02	4.3
B16	20.4	45.69	2.68
B17	17.58	47.85	5.62
B18	26.6	43.04	5.48
B19	36.6	42.94	2.5
B20	33.17	51.8	2.1
Average	28.52	45.25	2.86

MT = Total content of pale-colored and blue green amphibole, epidote and garnet; GM = Total content of zircon, tourmaline, staurolite; MF = Total content of pyroxene and hornblende.

Fig. 3. A. Relationship between ultra-stable and metastable minerals in the Mukdadiya Formation (after Pettijohn, 1975); B. Ternary diagram of heavy mineral stability of the Mukdadiya Formation samples based on Kasper et al. (2008)

Fig. 4. Ternary plot of the MF-MT-GM suite of the studied Mukdadiya Formation sandstone samples (after Nechaev and Isphording, 1993)

5. Conclusions

The heavy mineral assemblages in sandstone sediments from the Mukdadiya Formation are mainly represented by opaque minerals, epidote, amphibole, pyroxene, garnet and chlorite. According to the diversity of the heavy mineral, the sediments are derived from essentially sedimentary rocks followed by igneous and metamorphic rocks. The high contents of unstable and metastable minerals confirm their direct derivation from the adjacent primary source. The relationship between ultra-stable and metastable heavy minerals, indicates immature and moderate stability of sandstone sediments of the Mukdadiya Formation. Generally, they were transported from short distances and accumulated close to their source area and not represents polycyclic grain. The tectonic setting of the area was indicated from the MF-MT-GM ternary diagram that reflects the active continental margin was $MF > GM$ in the sediments.

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