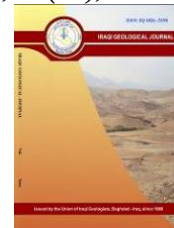




Iraqi Geological Journal

Journal homepage: <https://www.igi-iraq.org>



Petrography and Heavy Minerals as Tools for Provenance Identification of the Injana Sandstone (Upper Miocene), Al-Habbaniyah City, Anbar Governorate, Iraq

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Received:
12 September 2023

Accepted:
14 November 2023

Published:
29 February 2024

Abstract

This study deals with the petrography and heavy mineral analysis of the Injana sandstone at Al-Habbaniyah City. Thirteen samples are collected from the Injana Formation. A petrographic study is achieved on ten samples while all samples are analyzed for heavy minerals. The petrographic analysis showed that the common components of the Injana sandstone are rock fragments, especially sedimentary fragments. Quartz grains (monocrystalline and polycrystalline) and feldspars (k-feldspar and plagioclase), bounded by matrix and carbonate cement. The suggested provenance for the Injana Formation is mainly sedimentary and igneous sources and the less dominant metamorphic source. These sandstones are considered to be mineralogically submature-immature and classified as litharenites. Heavy minerals analysis showed two sets of minerals including opaque and transparent minerals, the opaque minerals are significant components of the heavy mineral assemblages, then chlorite, epidotes, amphiboles, garnet, pyroxenes (ortho and clino), zircon, tourmaline, biotite, muscovite, rutile, and others. This assemblage implies that the dense minerals are typically found in basic igneous and metamorphic rocks, with less frequent occurrences in acidic igneous and reworked sediments. According to QLF and QmFLt classifications, the tectonic provenance of the Injana sandstone is described as recycled orogen. The MF-MT-GM classification showed that the sandstone of Injana is derived primarily from active continental margins. The result of maturity MI and ZTR revealed low values of maturity, the MI value ranges between 0.6 to 1.5 with an average of 0.9 and ZTR Maturity ranges between 0.7% and 9% with an average of 3.9%, these low values of maturity indicate sub-mature to immature sandstone.

Keywords: Heavy Minerals; Injana; Upper Miocene; Al-Habbaniyah City; Iraq

1. Introduction

Injana Formation (Upper Miocene) is widely exposed in Iraq. Sandstone, siltstone, mudstone, and limestone make up the Injana Formation in a fining-upward sequence (Jassim and Goff, 2006). The lower fine-grained molasses sediments are represented by the Injana Formation, which first formed in the marine environment before gradually spreading to river and lake environments (Buday, 1980). Many researchers have studied the Injana Formation (Al-Juboury, 1994; Al-Juboury, 2009; Al-Juboury et al., 2009; Awadh and Al-Ankaz, 2016; Al-Salmani and Tamar-agma, 2018; Elias and Sissakian, 2022), while

DOI: [10.46717/igi.57.1B.2ms-2024-2-11](https://doi.org/10.46717/igi.57.1B.2ms-2024-2-11)

the current study is concerned with the petrographic description and provenance determination of the Injana Formation in Al-Habbaniyah City.

Petrographic characters of sandstone give a basic tool for their classification and with combination with other parameters it can be used to solve many sedimentological problems. The composition of sandstone is affected by the characteristics of the source, the nature of sedimentary processes within the depositional basin, and the type of path that connects the source to the basin (Dickinson and Suczek, 1979). Understanding and interpreting the origin of the sediment and the tectonic setting need the use of petrographic information, hydrodynamically controlled and diagenetically influenced sediment composition associated with sediment transport and deposition (Gupta and Pickering, 2008).

The mineralogy of the sandstone offers crucial information regarding its formation, including parent rock, lithology, and transportation history. Quartz, feldspar, and lithic fragments are the main components of sandstones, although they can include small amounts of other mineral grains, such as heavy minerals to deduce the source area composition.

Heavy mineral analysis is one of the most accurate and extensively applied methods for determining the origin of sandstones. The heavy mineral assemblage is influenced by several other activities that take place during the sedimentation cycle in addition to the mineralogy of the source region (Shehata et al., 2010). The studied area is located in Anbar Governorate in Al-Habbaniyah City near the old road linking Baghdad and Ramadi, at the longitude 43° 28' 27" E, latitude 33° 24' 11" N, where the formation is exposed (Fig. 1).

The studied section is 20 m thick and consists of sandstone, siltstone, limestone, marly limestone and thin bed of secondary gypsum. The work aims to provide a comprehensive petrographic description of the sandstones at Al-Habbaniyah City and to use the heavy minerals to interpret the provenance and tectonic.

2. Geological Setting

The studied area is situated within the Arabian Platform Mesopotamian Fore deep, Mesopotamia Subzone (Fouad, 2015). The Injana Formation (Upper Miocene) is a part of Tectonostratigraphic Megasequence AP11 (Latest Eocene to Recent). The succession of sediments between the unconformity marking the beginning of the Red Sea rifting and the initial collision of the Arabian and Eurasia plates is referred to this megasequence, and the present-day topographic surface (Beydoun, 1993). The transition from marine to lacustrine and fluvial sedimentation occurred gradually over the Upper Miocene-Pliocene cycle. This transition was accompanied by the clastics deposited during the cycle and coarsened gradationally. The growing mountain in northeastern Iraq was the primary source of the clastics (Buday, 1980). The source region of the sediment is mostly the highlands in the north and north-east of Iraq. The last gypsum layer appears at the lower contact of the formation with the underlying Fatha Formation in the region under study. The upper contact grades into Quaternary deposits. As the Miocene-Pliocene epoch approached its end, the Sanandaj-Sirjan region and the Neotethyan terrane collided with the Arabian Plate, causing large thrusts, the northern thrust zones grew as a result of this event as high and thrust high as in the northeastern portion of the Balambo-Tanjero and Mesopotamia zones. Throughout the Late Miocene and especially from the Pliocene, with increasing intensity, the upper fold region was raised; the surrounding Molasses Basin has been affected by erosion (Jassim and Goff, 2006).

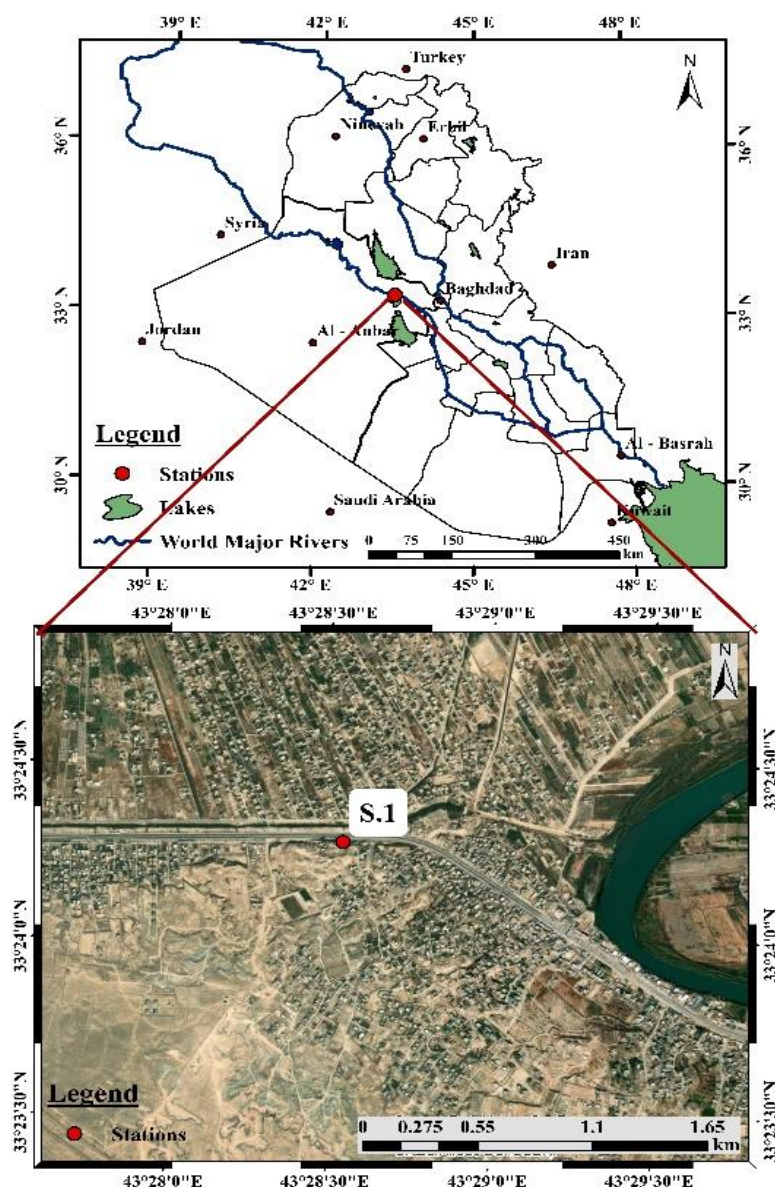


Fig. 1. Location map of the study area

3. Materials and Methods

Thirteen different samples of sandstone are collected from the Injana Formation. Ten thin sections are prepared and studied petrographically under a transmitted polarizing microscope. According to Chayes (1949), the percent of various components is computed by applying the point counter mechanical stage to count 300 grains in each thin slice. Grain disaggregation is the first step in the study of heavy minerals. A dense liquid with a density of 2.85 is used to separate heavy minerals from one another. Separated heavy mineral granules are placed on a glass slide for conventional investigation, which includes identification and counting using transmitted light microscopy (Carver, 1971).

4. Petrography

4.1. Light Minerals Petrographic Description

The Injana sandstone varies in size from fine to medium, grains are mostly subangular to subrounded shape. Quartz, rock fragments, feldspar, and carbonate cement make up the majority of the Injana sandstone's detrital components, these components are bound with matrix and carbonate cement.

Table 1. Modal analysis, range and mean constituent and MMI and MI Maturity Index of the sandstone at Al-Habbaniyah City

Locality	Formation	Sample No.	Quartz		Feldspar		Rock Fragments					Others%	MMI Maturity Index	MI Maturity index
			Mono. Quartz%	Poly. Quartz%	Plagioclase %	K-Feldspar%	Chert .R.F.%	Carbonate. R.F. %	Argillaceous R.F. %	Sandstone and Silt. R.F. %	Carbonate Cement. %			
Al-Habbaniyah City	Injana Formation	H.I.1	29.3	7.3	0.8	0.9	19.7	17.1	3.8	1.7	15.4	3.9	2.3	0.8
		H.I.2	22.1	6.6	2.7	2.1	15.4	21.5	1.4	2.0	21.6	4.4	1.5	0.6
		H.I.3	29.2	7.1	3.6	1.6	14.6	20.9	3.1	1.8	13.9	4.1	1.6	0.8
		H.I.4	32.9	4.2	2.1	2.3	15.7	14.3	2.6	2.1	17.9	6.0	2.3	0.9
		H.I.5	23.3	6.1	3.4	3.4	12.6	30.5	0.6	1.0	14.0	5.1	1.1	0.6
		H.I.6	21.7	11.9	2.9	1.5	11.9	18.6	2.7	3.2	21.5	4.0	1.6	0.8
		H.I.7	32.6	8.7	3.1	2.7	7.3	15.5	3.5	2.1	17.6	6.9	1.8	1.2
		H.I.8	35.4	12.3	4.8	4.3	9.9	10.5	2.4	0.3	13.1	6.7	2.6	1.5
		H.I.9	24.7	9.1	5.1	3.1	21.4	8.2	1.6	1.0	21.7	4.1	2.9	0.8
		H.I.10	33.2	5.7	2.9	1.3	15.6	16.7	0.9	2.5	15.5	5.8	2.2	1.0
		Range	21.7-35.4	4.2-12.3	0.8-5.1	0.9-4.3	7.3-21.4	8.2-30.5	0.6-3.8	0.3-3.2	13.1-21.7	3.9-6.9	1.1-2.9	0.6-1.5
		Mean	28.44	7.9	3.14	2.32	14.41	17.38	2.26	1.77	17.22	5.1	1.8	0.8

Quartz is considered the main component of the sandstone of the Injana Formation, with a total percentage ranging between 25.9–47.7%, with an average of 36.3%. It is characterized by the presence of two types: polycrystalline and monocrystalline quartz. The monocrystalline type ranges between 21.7–35.4 % with an average of 28.44 % and has fine crystals, angular to subangular form, and clear rim, with linear extinction. The polycrystalline type ranges between 4.2–12.3 % with an average of 7.9 % is also subangular to subrounded shape, wavy extinction, and its granules are larger than monocrystalline quartz in size. Most quartz grains have a subangular shape indicating a short to moderate transportation distance (Fig. 2). Feldspar is the least common mineral among the main constituents of Injana sandstone, its total percentage in the present sandstone ranging from 1.7–9.4 % with a mean of 5.89. Alkali feldspar (orthoclase and microcline) predominates in the feldspar, with plagioclase being less common. The majority of the feldspar grains are fresh, suggesting a dry to semi-dry environment (Fig. 2). Rock fragments are common and represent a high percentage of the constituent of Injana sandstone, the content of which varies between 16.4 and 58.9%, with a mean of 35.82%. Chert, carbonate, argillaceous, and sandstone are among the Sedimentary rock fragments that comprise most of the Injana sandstone. Less common are other types of rocks (such as igneous or metamorphic). Chert rock fragments are the most abundant, followed by carbonate fragments. Compared to the other sandstone components, the rock pieces are often coarser and have a subangular-subrounded form, indicating a short transport distance (Fig. 2). The Injana sandstone contains between 13.1% and 21.7%,

with a mean of 17.22% carbonate cement. The research being done shows that the Carbonate cement has a high concentration and fills in the voids left by the residues (Fig. 2).

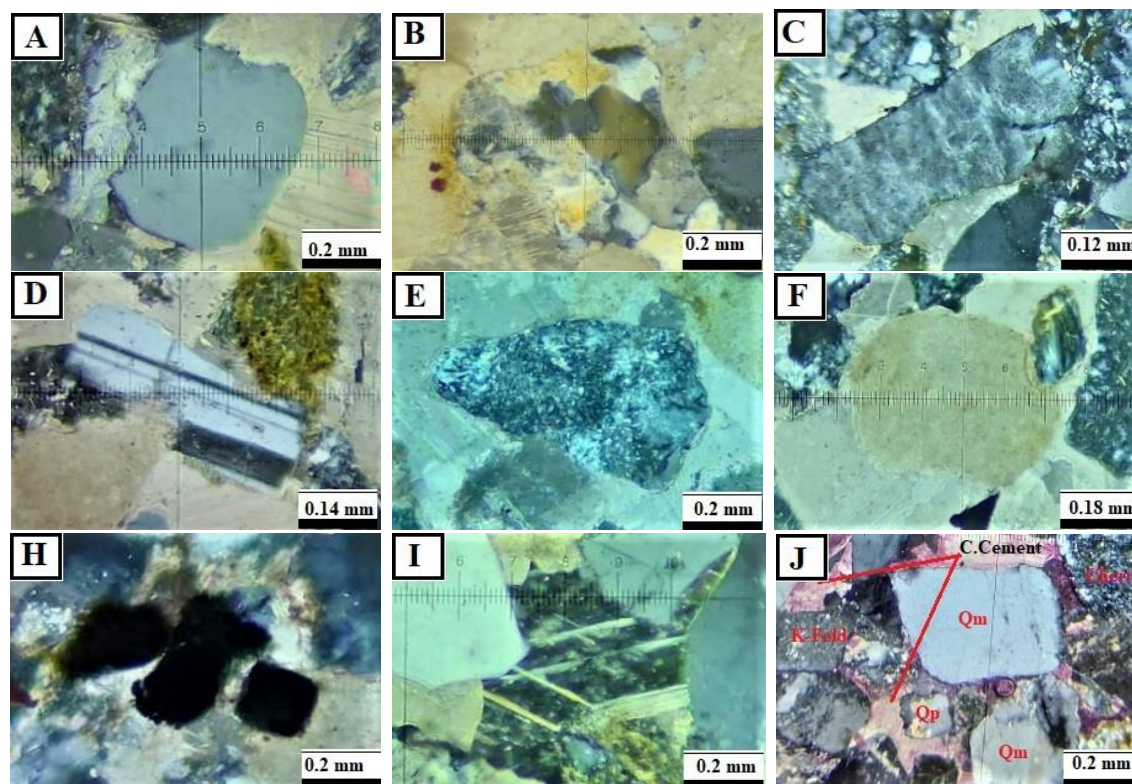


Fig. 2. Photomicrographs (Crossed Nicol) of the detrital grains in Injana sandstone (Habbaniyah): A: Monocrystalline Quartz (straight extinction), B: Polycrystalline Quartz, C: Orthoclase, D: plagioclase, E: chert, F: carbonate fragments, H: Opaque Minerals, I: Metamorphic Rock Fragment, J: Mono, polycrystalline quartz, chert and orthoclase binding by Carbonate Cement

4.2. Heavy Minerals

Injana sandstone has two distinct groups of heavy minerals, which may be distinguished by color into transparent minerals and opaque minerals (Fig. 3). Opaque minerals represent the essential components, opaque minerals are generally angular to sub-rounded, and their shape is generally equidimensional. Their percentage ranges from 16.5 to 43.1%, with an average of 29.8% of the total heavy minerals (Table 2). Transparent heavy mineral groups include stable, metastable, and unstable heavy minerals, and their general characteristics and average are as follows: chlorite is the most common among transparent heavy metals. It is characterized by a grassy green to dark green color and is often rounded in shape with an average of 17.6%. The epidotes rank second among the transparent minerals. Its color is olive green and its shape is often rounded, with an average of 12.6%. Garnet is colorless to pink and is optically homogeneous. The shape of the grains is mostly sub-angular to sub-rounded, with an average of 9.7%. Amphibole is characterized by the appearance of color pleochroism and the shape of its grains is usually prismatic, containing the phenomenon of cockscomb, with an average of 10.8%. Pyroxene exists in two types of clinopyroxene (CPX) and orthopyroxenes (OPX), characterized by green color and sub-rounded prismatic grains, with a total average of 13.1%. Biotite is characterized by a brown color and strong pleochroism, with a tabular grain shape, its average is 1.1%, muscovite is colorless, tabular shape with an average of 0.8%, Tourmaline is characterized by honey color and strong pleochroism, with an average of 1.1%, rutile characterized by dark red color with black halo and

elongate shape, its average is 0.3%, and others (including undifferentiated and less than 0.2%) 2%. The percentage, range, and average of heavy minerals is shown in (Table 2).

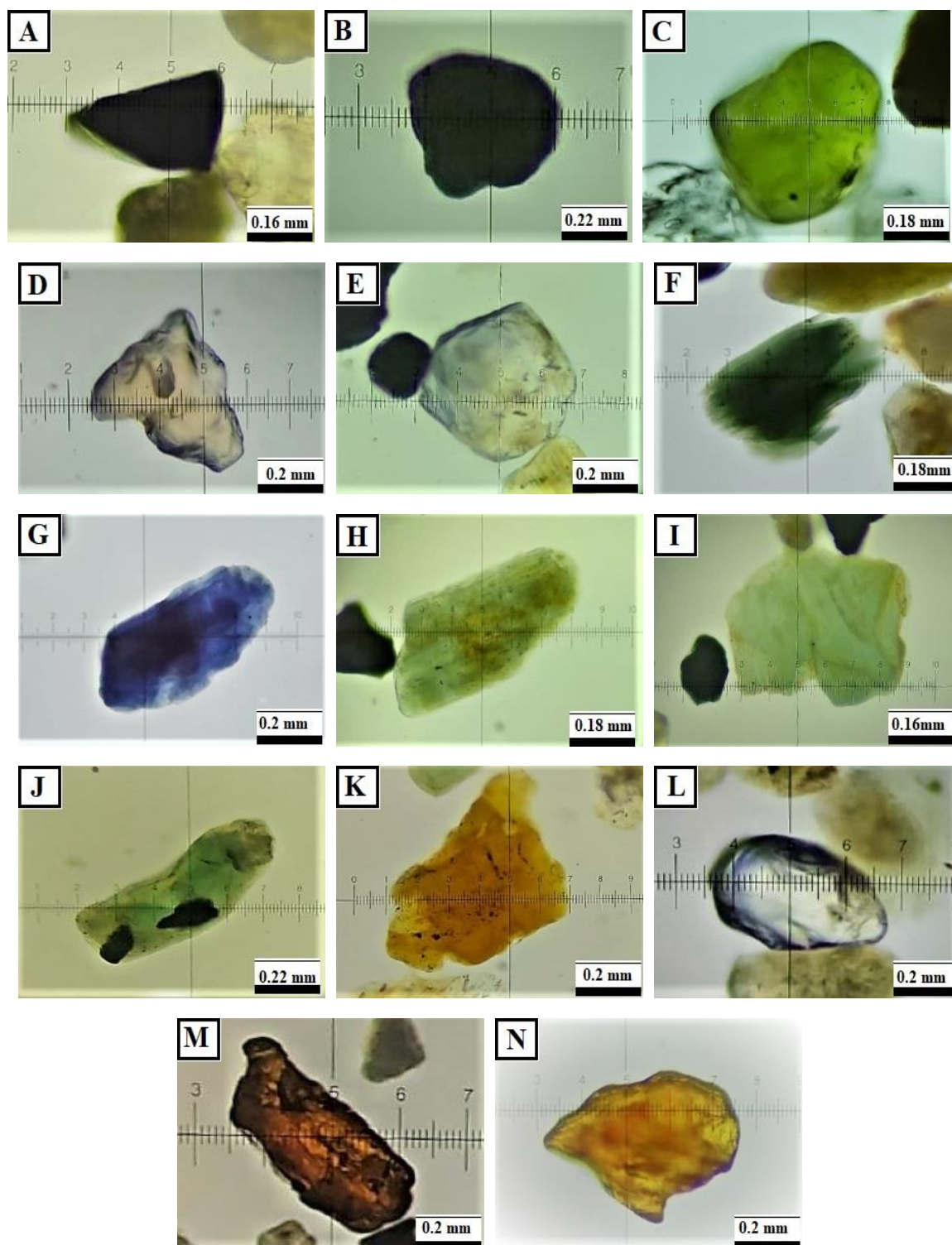


Fig. 3. Photomicrograph of the heavy minerals of the Injana sandstones: A) Angular opaque mineral, B) Rounded Opaque, C) Epidote, D & E) Garnet, F) Pleochroic amphibole (hornblende), G) Pleochroic amphibole (glaucophane), H) pyroxene, I) Chlorite, J) Chlorite with opaque inclusion, K) Biotite, L) Zircon, M) Rutile, N) Staurolite

Table 2. Modal analysis, range, average, and ZTR Maturity index of heavy minerals of Injana sandstone at Al-Habbaniyah City

Sample No.	Opaque %	Unstable Minerals			Metastable Minerals		Ultrastable Minerals			Flaky Minerals				ZTR Maturity Index
		Amphibole %	CPX %	OPX %	Epidote %	Garnet %	Tourmaline %	Zircon %	Rutile %	Chlorite %	Biotite %	Muscovite %	Others %	
A.I.1	16.7	9.6	7.0	5.4	17.7	11.4	0.9	0.8	0.4	27.6	0.8	1.8	0.0	2.5
A.I.2	43.1	5.8	4.8	3.0	19.1	8.6	0.6	2.2	0.5	11.1	1.2	0.0	0.0	6.0
A.I.3	23.7	19.7	10.4	8.0	11.3	11.8	1.0	2.4	0.4	8.3	0.0	2.9	0.2	5.2
A.I.4	37.4	13.5	8.4	5.6	7.2	8.8	1.5	0.9	0.7	15.4	0.2	0.4	0.0	5.2
A.I.5	16.5	14.4	12.0	7.5	13.6	6.5	0.6	0.4	0.6	23.6	1.5	0.7	2.1	2.1
A.I.6	35.7	6.6	4.0	4.7	13.7	7.7	2.5	2.7	0.2	19.8	0.0	0.8	1.7	9.0
A.I.7	35.0	6.5	3.9	3.4	15.6	11.2	0.9	0.4	0.3	16.2	2.8	0.9	2.8	2.4
A.I.8	35.2	9.8	6.4	7.6	15.1	11.4	0.5	0.0	0.2	9.1	1.3	0.7	2.6	1.0
A.I.9	31.6	8.5	5.6	5.2	8.4	13.0	0.6	1.7	0.1	21.9	0.0	0.3	3.2	3.5
A.I.10	24.8	10.0	6.9	7.3	14.4	11.3	1.7	0.0	0.0	20.1	0.9	0.7	1.9	2.3
A.I.11	31.2	12.3	8.3	6.5	7.3	5.9	0.3	1.7	0.3	21.8	0.3	0.6	3.6	3.5
A.I.12	38.6	8.8	6.8	1.9	7.8	9.7	2.8	1.1	0.0	14.0	3.4	1.0	4.1	6.8
A.I.13	18.6	14.6	8.9	10.8	12.1	9.0	0.6	0.0	0.0	20.3	1.3	0.3	3.5	0.7
Range	16.5	5.8-	3.9-	1.9-	7.2-	5.9-	0.3-	0.0-	0.0-	8.3-	0.0-	0.0-	0.0-	0.7-
Averag	29.8	10.8	7.2	5.9	12.6	9.7	1.1	1.1	0.3	17.6	1.1	0.8	2.0	3.9

5. Classification of Injana Sandstones

The Folk (1974) classification was used to identify the type of sandstone in the Injana Formation, depending on the proportion of the main sandstone component which includes quartz, feldspar, and rock fragments (Table 3). As a result of this classification, it was found that all the samples were considered litharenite in the Injana sandstone (Fig. 4). Since the composition of litharenites is immature, this suggests that sediment is transported across short distances and rapidly deposited from sources (Tucker, 1985). Boggs (1995) mentioned that litharenites are a type of compositionally immature sandstone that forms when a lot of moderately unstable minerals are produced and deposited.

Table 3. The main component of Injana sandstone recalculated to 100% for classification purpose

Sample No.	Quartz%	Feldspar%	Rock Fragment%
H.I.1	70	2	28
H.I.2	60	7	33
H.I.3	62	6	32
H.I.4	69	6	25
H.I.5	52	8	40
H.I.6	61	6	33
H.I.7	64	8	28
H.I.8	72	11	17
H.I.9	74	11	15
H.I.10	69	5	26
Range	52-74	2-11	15-40
Average	65.4	7.1	27.5

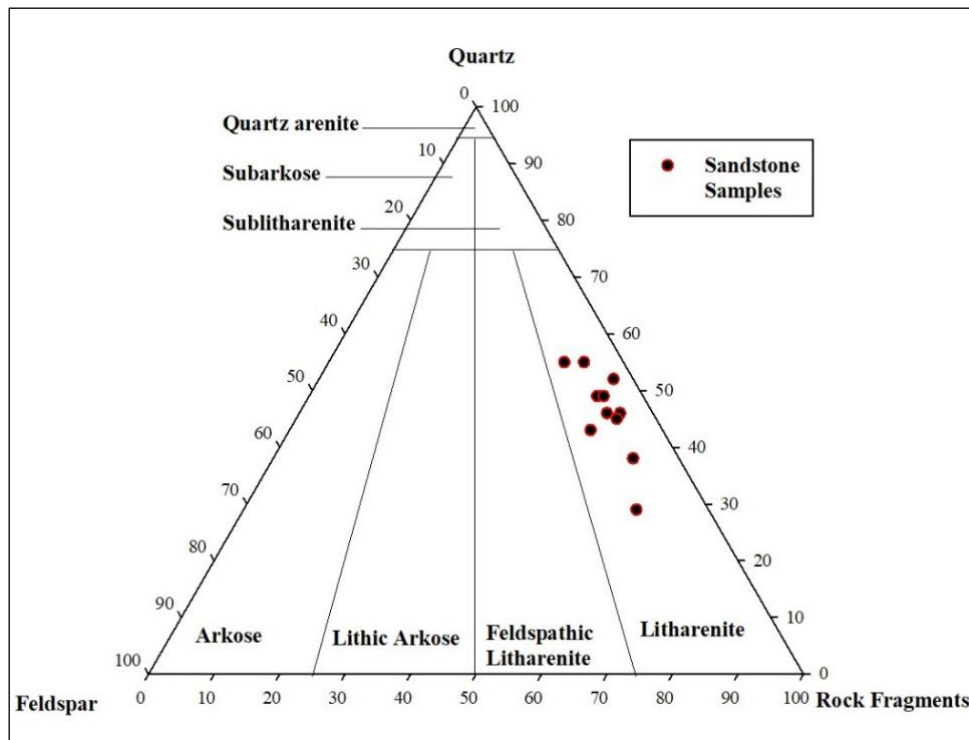


Fig. 4. Injana Sandstone Classifications at Al-Habbaniyah City (after Folk, 1974)

6. Maturity of Injana Sandstone

6.1. Compositional Maturity

Compositional maturity is defined as the difference between the amount of relatively stable grains and those that are unstable (Boggs, 2006). In this work, the mineralogical maturity is determined using two formulas.

$$\text{Maturity index (MI)} = \frac{Q}{F+R.F} \quad \text{----- (1)}$$

(Pettijohn, 1975), where Q: Quartz, F: Feldspar and R. F.: Rock Fragments

$$\text{Mineral maturity index (MMI)} = \frac{Q+Ch}{F+R.F} \quad \text{----- (2)}$$

(Pettijohn, 1957), where Q: Quartz, Ch: Chert, F: Feldspar and R. F.: Rock Fragments

When the first formula was used, the results presented that the mineral maturation values for Injana were between 0.57 and 1.48 with an average of 0.91. The second formula was applied since the chert content was so high, the results of the analysis indicated that the mineral maturation values of the Injana sandstone ranged from 1.08 to 2.9, with a mean of 1.99 (Table 1) indicating low to moderate compositional maturity (sub-mature-immature sandstone) for the Injana sandstone.

6.2. ZTR Maturity Index

The ZTR index provides a quantitative definition of the heavy mineral assemblages' mineralogical maturity. The proportion of mutual zircon, rutile, and tourmaline grains in clear, non-micaceous, detrital heavy minerals is known as the ZTR index (Hubert, 1962). The Hubert method is used to find the ZTR index for each sample according to the following equation:

$$\text{ZTR Index} = \frac{\text{Zircon} + \text{Tourmaline} + \text{Rutile}}{\text{Total number of non-opaque heavy minerals}} * 100 \quad \text{----- (1)}$$

The examined samples of the Injana sandstone have ZTR maturity index values between 0.7% and 9% with an average of 3.9% (Table 2). These low values of the ZTR index indicate immature sediments of the Injana sandstone.

7. Provenance Determination

The nature of the sedimentary origin, the sedimentary processes that occur within the sedimentation basin, and the types of dispersal pathways that connect the source to the basin all influence sandstone formation (Dickinson and Suczek, 1979). Patterns of the sandstone component reveal details about the formation and tectonic conditions of the source (Dickinson et al., 1983). In the present work, heavy mineral analysis, petrographical model analysis, QFL, and QmFLt tectonic classification diagrams were used to determine the source of the sandstone.

7.1. Determination of Provenance from Light Minerals Analysis

The majority of provenance investigations are based on the petrographic study of quartz, feldspar, and rock fragments (Boggs, 2009). Quartz is a key mineral that makes up sandstone because of its chemical stability, absence of cleavage, and comparatively high hardness. The presence of quartz in the rock results from several sedimentary cycles (Boggs, 1997).

This study primarily shows plutonic igneous rocks by the existence of monocrystalline quartz with undulate extinction ranging from straight to oblique (Basu, 1985). Undulate extinction $> 5^\circ$ degree, which is the highest level of undulate quartz, is indicative of metamorphic rocks (Folk, 1974). The monocrystalline quartz's undulate extinction and some of its grains' disintegration under stress could be a sign that it came from plutonic igneous and metamorphic rocks (Asiedu et al., 2000). Polycrystalline quartz has intercrystalline borders that are usually straight or slightly curved, which indicates plutonic origin (Tucker, 1985). Some grains have suture intercrystalline boundaries, which points to their metamorphic origin (Folk, 1974).

Feldspar is considered more important to know the source than quartz because it is less stable in both physical and chemical states (Boggs, 2009).

According to Pittman (1970), Orthoclase and Plagioclase can come from both plutonic igneous and metamorphic rocks, although microcline and perthite are more prevalent in plutonic igneous rocks, and rarely in rocks from volcanoes. An additional feldspar presence may indicate a fragmentation process from igneous rocks accompanied by a short distance of transportation (Pettijohn, 1975).

Because it may come from several types of rocks, a piece of rock is important to study the origin and is more reliable than studying individual minerals such as quartz and feldspar (Boggs, 1997).

Chert rock pieces can come from carbonate formations that include chert nodules as well as Chert in the north-eastern thrust zone sequence, particularly the Qulqula Group (Al-Juboury, 1994).

The Arabian Shelf underlying Mesozoic carbonate rocks are most likely the source of the carbonate rock fragment, which is thought to have originated from adjacent locations. Rock pieces from carbonate sources exhibit a unique type of fast mechanical corrosion rather than chemical disintegration (Pettijohn et al., 1987), the occurrence of a high rate of carbonate rock piece in the Injana Formation indicate that the source rock is essentially carbonate rocks, this fragment existence in the sediments suggests that the material was transported locally and quickly (Al-Juboury, 1994). Rapid erosion and incomplete weathering were necessary due to the existence of volcanic rock pieces; these conditions only exist in places with high relief and dry climates (Pettijohn et al., 1973). Dickinson (1985) suggested that these pieces could have come from the thrust zone. According to Takin (1972), the Sanandaj-Sirgjan zone and the northeastern thrust zone where the metamorphic rock pieces are most likely to have come from.

7.2. Determination of Provenance from Heavy Minerals Analysis

Heavy minerals have been widely used to determine transport and provenance signature in several depositional environments such as dunes, beaches, alluvial deposits, and rivers (Kasper-Zubillaga et al., 2008). Heavy mineral is typically used for source rock determination (Boggs, 2001). Heavy minerals data offer limitations on the mineralogical nature of the source terrains (Morton and Hallsworth, 1999). The provenance rocks and tectonic construction must be identified to determine the provenance., heavy minerals are analyzed. According to Blatt et al. (1972), In this research, "opaque" is used to refer to mafic rock, metamorphic rock, acidic rock, and sedimentary rock that's been reworked (Tucker, 1991). Pyroxene is good evidence of mafic igneous rock and metamorphic rock in the provenance area, glaucophane is one of the unique minerals found in metamorphic rocks like gneiss or schist (Boggs, 1995), Hornblende is a type of mineral that can be found in a lot of different types of rock like mafic rock and even metamorphic rock biotite is derived from an acidic igneous rock (Milner, 1962). The minerals epidote, staurolite, kyanite, silliminite, garnet, and amphiboles, including glaucophane and tremolite-actinolite are mostly derived from metamorphic sources (Milner, 1962). According to Force (1980), the occurrence of rutile is indicative of the provenance of acidic igneous rock and high-grade schist metamorphosed argillaceous sediments. Tourmaline indicates granitic pegmatites and an acidic igneous source (Pettijohn et al., 1987). Rounded or subrounded grains, such as certain, zircon, opaques, and tourmaline, are a sign of reworked sedimentary provenance (Greensmith, 1988). Based on the findings of the heavy minerals analysis for the samples being looked at, the parent rocks of the Injana Formations are typically mafic, ultra-mafic, and metamorphic, in addition to acidic igneous and reworked sedimentary origin.

7.3. Tectonic Setting of Provenance

Terriigneous sedimentary rocks were separated into three major tectonic settings, consisting of the continental block, the magmatic arc, and the recycled orogen, by Dickinson and Suczek (1979) and Dickinson et al. (1983), these are mostly based on the petrographic characteristics of rocks with a particular provenance. To distinguish the three main tectonic settings of sediment Dickinson et al. (1983) and Dickinson and Suczek (1979) suggested a ternary composition diagrams (QFL and QmFLt) for classification of tectonic provenance, where; Q, total quartzose, F, Total Feldspar, L, total unstable lithic fragment. Monocrystalline Quartz (Qm) Feldspar (F) and Lt for both polycrystalline quartz and unstable lithic fragment). All of the Injana sandstone samples on the QFL diagram clumped in the field of recycled orogen (Fig. 5). All samples on the QmFLt diagram fell into the transitional recycled field (Fig. 6). The term "recycled orogens" refers to the initial orogens that are created by the unfolding or upfaulting of sedimentary or metasedimentary terrains, allowing the recycling of the rock debris into related basins. This is akin to what is present where the Taurus and Zagros Mountain ranges collide. Many recycled orogen was generated by the collision of terrains that were formerly different continental blocks (Boggs, 2012).

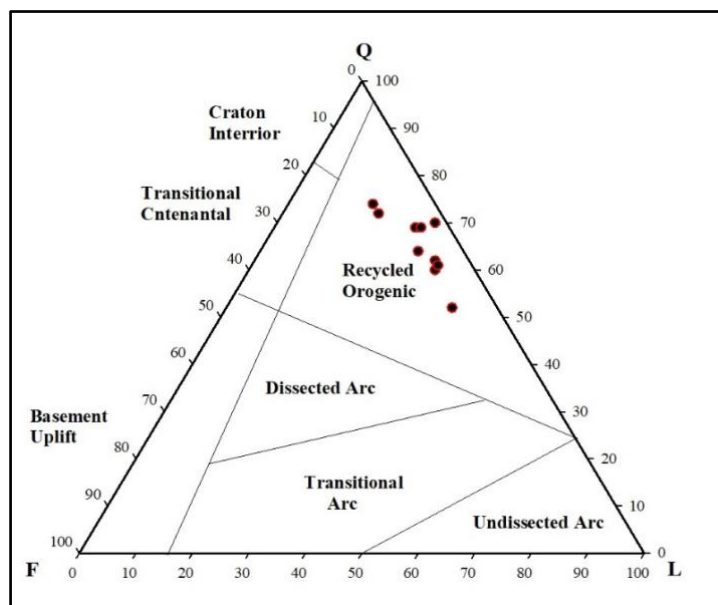


Fig. 5. QFL ternary diagram illustrating the origin of the Injana sandstone after (Dickinson et al., 1983)

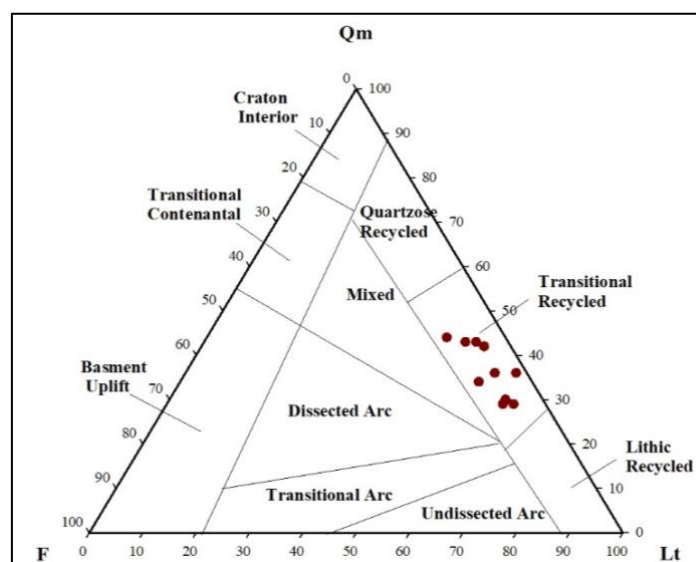


Fig. 6. QmFLt ternary diagram illustrating the provenance of the Injana sandstone tectonic region after (Dickinson et al., 1983)

8. Heavy Mineral Assemblage and Continental Margin Activity

It has long been understood that tectonic activity and sediment type are related (Pettijohn et al., 1987). By contrasting the assemblage with probable clastic sediment sources originating from various stages of the plate tectonic cycle, Nechaev and Isphording (1993) proposed a plate tectonic interpretation based on heavy mineral data, and they created a triangular diagram of GM, MF, and MT relationship between the heavy mineral assemblage and the plate tectonic environment where:

MF: common constituents of mafic magmatic rocks; total contents of pyroxene, hornblende, and olivine.

MT: Epidote, garnet, and total amounts of light-colored and blue-green amphibole are the main components of basic metamorphic rocks.

GM: Zircon, tourmaline, staurolite, kyanite, andalusite, monazite, and sillimanite are all accessory minerals found in granites and sialic metamorphic rocks. Plotting of the samples of sandstone on the

ternary diagram (Fig. 7) shows that all samples are located within the area of active continental margins which contain a relatively high proportion of basaltic minerals. The Taurus Highlands and the Zagros Mountains could serve as representations of this source rock.

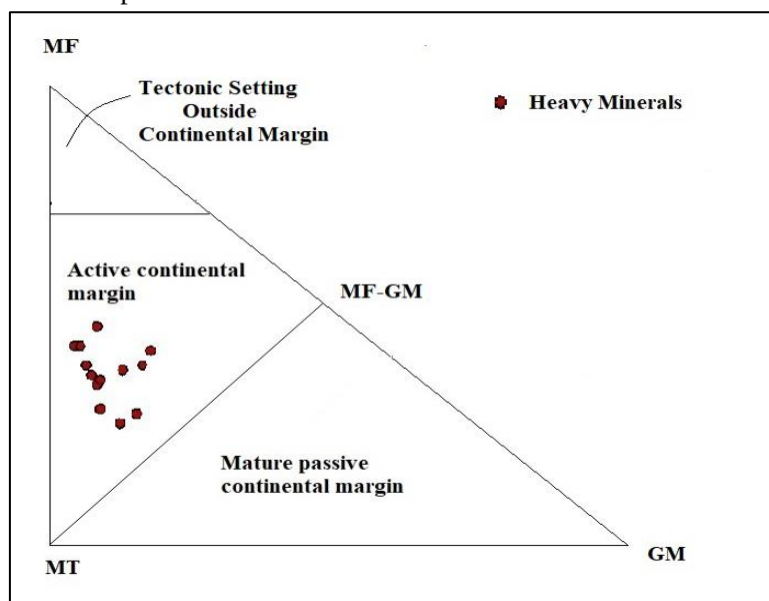


Fig. 7. Relationship between the Injana sandstone MF-MT-GM suites (after Nechaev and Isphording, 1993)

9. Conclusions

Monocrystalline quartz is more common than polycrystalline quartz and possesses characteristics that indicate it is mostly composed of reworked sediment and plutonic igneous rock. Plagioclase is less frequent than k-feldspar (orthoclase and microcline), and it frequently has plutonic igneous and metamorphic origins. The ratio of rock fragments to quartz and feldspar is high, indicating a low effect of diagenesis and a low distance of transportation. Recycled sediments are indicated by the great amount of sedimentary fragments compared to metamorphic and igneous fragments. The sandstone of the Injana Formation, classified as litharenite, has high relief, erodes quickly, and is located close to its source. It contains various heavy minerals, indicating different source rocks. In comparison to other heavy minerals, the heavy minerals assemblages have a relatively high proportion of opaques, which are thought to originate mostly from sources of basic igneous rock and metamorphosed rock as well as from sources of acid igneous rock and altered sediment. Heavy, unstable minerals are an indicator of nearby igneous rock sources. Active continental edges, which exhibit a relatively high proportion of mafic minerals, are where the heavy minerals are found. The totaled mineral maturity MMI, MI, and ZTR maturity index showed that the Injana sandstones are mineralogically immature-submature. The primary framework mineral composition of the Injana sandstone indicates that the detritus of the deposits is derived from a recycled orogen, with provenance in the transitional and lithic recycled regions. The tectonic setting of the source areas according to the MF-MT-GM ternary diagram indicates that the sediments are derived from the active continental margin.

Acknowledgements

Many thanks to the locals who assisted with the fieldwork in the examined region., and I also do not forget my colleagues in the research who expressed their opinions on the interpretation of the results.

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