PETROGRAPHY AND DIAGENESIS OF THE HAWAZ SANDSTONE FORMATION, MURZUQ BASIN, SW LIBYA

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Abstract: Middle Ordovician Hawaz Formation represents the primary reservoir rocks in Murzuq Basin. In J Oil Field Hawaz Formation consists of a 550 feet thick succession made of fine-grained quartz-arenite displaying a variable degree of bioturbation. This J Oil Field study is an integration approach and it is based on 235 feet thick of slabbed cores photographs from well J4-NC186, with core samples, petrography, wireline log data, and conventional core analysis of the Hawaz siliciclastic sediments. The Hawaz Formation was deposited in wave-dominated shoreface and shelf environments. The stratigraphical and sedimentological characteristics of the Hawaz Formation in the study area in Murzuq Basin are attributed to shoreface and shelf facies associations within which some 9 facies have been distinguished. The lower part of the cored section of the Hawaz Formation is dominated by the outer and inner shelf facies associations. The outer shelf association is dominated by mudstone whereas, the inner shelf association is dominated by siltstone/sandstone.
Petrographic analysis provides a means of assessing the composition of the sandstone and relating this to their provenance, tectonic setting, diagenetic evaluation and economic potential (Pettijohn *et al*, 1987). Petrographic investigations show that Hawaz sediments can be divided into six categories: (a) rock fragments, (b) quartz, (c) feldspar, (d) micas and authigenic quartz, clay minerals and other constituents. Originated mainly from metamorphic rocks in humid climates.

Keywords: Hawaz Sandstone Formation, Murzuq Basin, Petrography, Diagenesis.

INTRODUCTION

General Overview of the Study Area

Murzuq Basin is located on the North African Platform, covers an area of some 350,000 km^2, extending southwards into Niger. Thomas (1995) mentioned that the present-day borders of the basin is defined by erosion resulting from multiphase tectonic uplifts (Fig. 1). It is not a sedimentary basin in the normally accepted sense and could more accurately be described as an erosional remnant of a much larger Palaeozoic and Mesozoic sedimentary basin which originally extended over much of North Africa.

The flanks comprise the Tihemboka High to the west, the Tibesti High to the southwest, and the Gargaf and Atshan highs to the north and north west. These uplifts were generated by various tectonic events ranging from middle Palaeozoic to Tertiary time, but the main periods of uplift took place during Middle Cretaceous to Early Tertiary Alpine movements. The present-day Murzuq Basin contains a maximum sedimentary fill of about 4000m. Davidson, *et al* (2000) pointed out that, despite successive erosive episodes during several phases of uplift and erosion throughout the history of the basin, the maximum sedimentary thickness probably never exceeded 5000m at any single point in time. Murzuq Basin has different concessions containing some oil fields, one of them is J Oil Field in concession NC186 in.

The petroleum system is represented by structural Hawaz paleo-high created during the post Hawaz erosional event, the main regional seal is the Silurian Tanezzuft shale Formation, and the basal Tanezzuft hot shale member acts as the main source rock in study area. This formation is considered the main target. The strata are faulted and the faults are most frequently parallel to the axis. Tectonic movements affected the basin to a greater or lesser degree from middle Palaeozoic, Oligocene (Alpine) times, Bellini and Massa, (1980). Hawaz Formation rests conformably over the Ash Shabiyat Formation. Both formations are cut by an erosive surface recognizable in outcrop and subsurface. Hawaz Formation is typically

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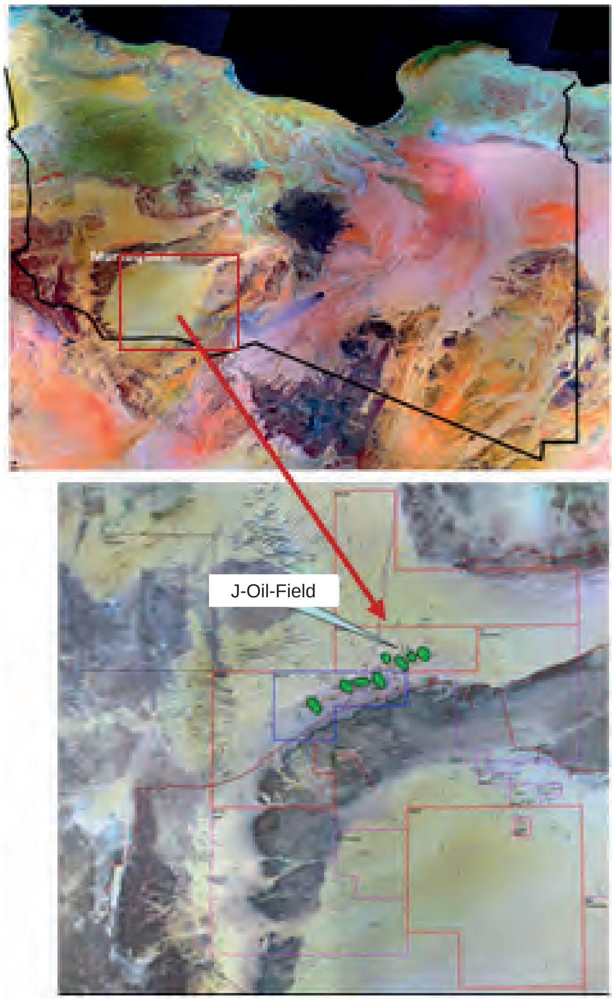

Fig. 1. Location map of J-Oil-Field in Concession 186, Murzuq Basin.

consisting of cross bedded, quartzitic sandstone with kaolinitic and thin shaley intercalations (Tigillites) bioturbated levels and ripple marks are conspicuous. The formation thickness ranges from 50 meters at Dor al-Qussah to 300 meters at Al-Qarqaf in outcrops, and 30 to 230 meters in the subsurface.

Location of the Study Area

Murzuq Basin is located at the southwestern part of Libya. Concession NC186 is in northwestern flank of the Murzuq Basin (Fig. 1).

Aims of the Study

To provide a detailed sedimentological description of the core from well J4-NC186. To integrate the sedimentological and thin section data in order to derive any variation of the mineralogical composition and diagenetic sequence which adequately account for the Hawaz Formation in the study well. The main objective of this study to: a) assess the mineral composition. b) Classify the sandstones. c) Reconstruct their diagenetic history, and d) determine the source rock provenance and composition.

Structure of the Area (J Oil Field)

J Field-NC186 is located in Murzuq Basin, SW Libya; in the middle southern part of NC186 block between H and B fields. J Field NC186 is an elongated NW-SE of Hawaz Paleo-High and tilted to the SE, associated with a 4 way dip structural closure. Middle Ordovician Hawaz Formation is the main reservoir in J Oil Field, the formation comprises a distinctive suite of facies associations representing a broad range of environments from low energy shelf marine sediments deposited largely below storm wave base, through to sub-aerial delta plain channel environments.

METHODOLOGY

The petrograpic study was provided by Akakus Oil Operation. This study is based on a total of 30 thin-sections, from J4-NC186. However, thin sections have been impregnated with blue resin in order to facilitate the microscopic examination of texture and quantitative analysis of composition and porosity. Because the mineralogy of a sandstone, is primarily inherited from the source area, modified by sedimentary processes and diagenesis, mineralogical examination provides one of the most useful approaches to obtain information about the provenance. These informations including tectonics and climate, the effects of transportation, including distance and direction, and the addition of minerals during sedimentation and diagenesis (Pettijohn *et al*, 1987).

The thin sections were analyzed using a point counter to determine the percentage of quartz, feldspar, rock fragments, heavy minerals, mica, kaolinite, calcite, pyrite, matrix and porosity. The analysis was carried out using a Swift automatic point counter and mechanical stage. Three hundred grains were counted per slide for statistically reproducible results and then the results recalculated to 100%. The porosity measurements were estimated by standard modal analysis techniques and the porosity in the Hawaz Formation classified into three types for counting purposes: primary porosity, secondary porosity and micro-porosity.

PETROGRAPHIC ANALYSIS RESULTS AND INTERPRETATION

Compositional Analysis

The model composition of the Hawaz Sandstone provides evidence of the composition of the source and the diagenetic events that affected the post depositional burial history of the sandstone.

The detrital particles in siliciclastic rocks in the Hawaz Sandstone in J4-NC186, have been divided into six categories: (a) rock fragments, (b) quartz, (c) feldspar, (d) micas, (e) heavy minerals and authigenic (f) clay minerals and other constituents.

Quartz: Quartz is the most common mineral in sandstone and the most physically and chemically stable under sedimentary conditions at the earth's surface.

In wells J4-NC186; Al-NC186 and H27-NC115, the Hawaz sandstones are composed mainly of quartz grain (Fig. 2), dominated by monocrystalline grains

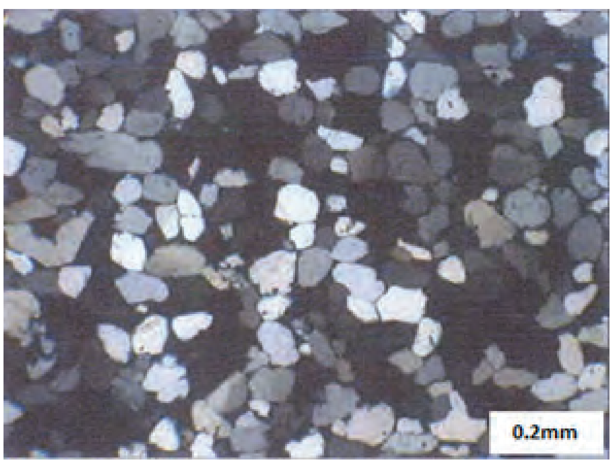

Fig. 2. Photomicrograph of a quartz arenite in the Hawaz Sandstone, which is dominated by monocrystalline quartz. XPL (X4).

(96 to 99%), relative to feldspar and rock fragments with some 2% of polycrystalline grains. Most of the quartz grains in the Hawaz sandstones in these wells show strong undulose extinction, which are more abundant in strained source rocks, especially metamorphic rocks. Also, the polycrystalline quartz grains are characterized by relatively straight boundaries between equant grains, and straight to slightly undulose extinction (Fig. 3).

The grain contact types in the Hawaz sandstones are related to the particle shape and packing. The packing depends on the spatial density of particles in a sediment accumulation. Most monocrystalline quartz grains have concavo-convex contacts, suggesting that these grains have undergone

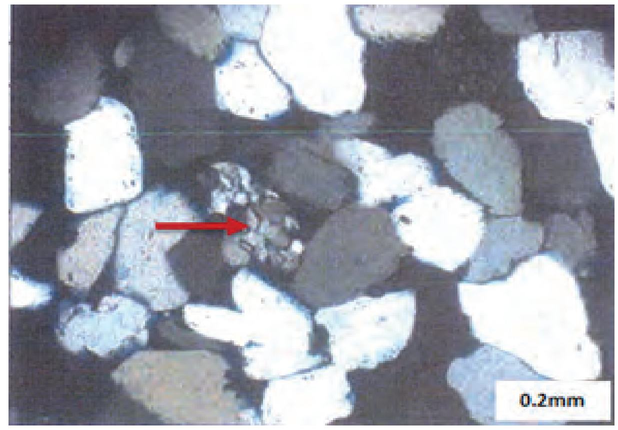

Fig. 3. Photomicrograph showing a metamorphic polycrystalline quartz grain. XPL (X20).

considerable compaction during burial. Sutured contacts are also recognized. These varieties of grain contact types can be used as a rough measure of the degree of compaction and packing, and thus the depth of burial of the sandstone.

Quartz overgrowths can be recognized in thin-section either by dust rims between detrital grains and the overgrowth, or by the development of excellent rhombohedral crystal terminations growing into pore space (Fig. 4).

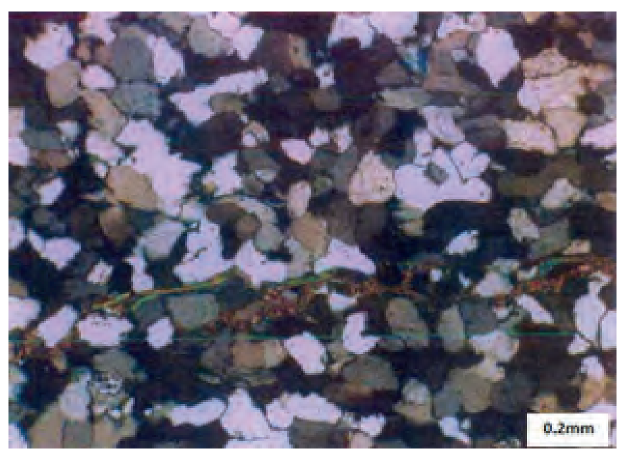

Fig. 4. Photomicrograph of quartz overgrowth, in which the quartz grew into the pore on one side which is not filled by clay minerals at the time, PPL, (Xl0).

Feldspar: The feldspar content in most sandstones averages between 10 and 15%, but in arkoses it may reach 50%. The mechanical stability of feldspar is lower than that of quartz, since feldspars are softer and have a stronger cleavage. This leads to disintegration of feldspar crystals during transportation, particularly in high energy depositional environments, so that on a broad scale, for example, fluviatile sediments contain more feldspar than beach or shallow marine sediments (Tucker, 1981). The alteration of feldspar has been considered to reflect climatic conditions prevailing at the time at the depositional site. Feldspar occurs nearly in all types of crystalline rocks, so that feldspar grains of sand-size can be derived from granitoid igneous rocks, gneisses and schists in large amounts. The percentage and type of feldspar m sandstone depends on the rate and type of tectonic activity, and climate.

Feldspars are the second most abundant mineral in most sandstones (Boggs, 1995). The complex nature of the feldspar minerals has resulted in their being subdivided into many categories on the basis of their chemical, physical and structural characteristics. The categories of feldspar normally used by sedimentary petrologists are: (i) potassium (orthoclase, microcline and sanidine); (ii) plagioclase (albite through anorthite); and (iii) perthite (an intergrowth of sodium feldspar and potassium feldspar) (Blatt, 1982). The relative proportions of K-feldspar and albitic and anorthic plagioclases may be controlled either by the relative abundance of those feldspars in the igneous and metamorphic source rocks or by differential stability at the earth's surface (Pettijohn *et al*, 1987).

The feldspars are the second most abundant detrital grain types in the Hawaz Sandstone ranging from traces to 9%. The bulk of the feldspar grains are either K-feldspar or microcline, with lesser amounts of plagioclase. The untwined orthoclase is characterized by low relief and cleavage.

Rock Fragments: Pieces of polymineralic source rock form 15-20% of the average sandstone but can supply much more than 15% of the provenance information about the rock (Blatt, 1992). The composition of the rock fragment depends basically on source-rock geology and durability of particles during transportation. In sandstone, the lithic fragments are commonly fine-grained sedimentary and metasedimentary rocks such as mudstones, siliceous sedimentary rocks such as chert, and igneous, volcanic rocks (Tucker, 2001). The coarser-grained source rocks will contribute mostly mineral grains but depending upon the ratio of the grain-size of the source rock to the grain-size of the sandstone, they may also provide rock fragments. Thus, the larger the grain-size of the sandstone, the more likely is the occurrence of rock fragments, and the better the assessment of source terrane lithologies (Pettijohn *et al*, 1987).

Rock fragments in the Hawaz Sandstone are present, but not common, ranging from traces up to 3% in wells J4-NC186; A1-NC186 and H27-NCI15. They consist of metamorphic polycrystalline quartz rock fragments or chert, with a few clays mineral fragments.

Mica: Sand-size detrital mica, because of its platy mature, would be expected to be the hydraulic equivalent of smaller particles of other minerals. As a result of the transportation and depositional characteristic of mica, its areal distribution in sediments reflects short-term response to environmental energy conditions. The absence of mica in recent sediments should indicate that either no mica is being contributed, or that energy conditions are such that winnowing, and/or by-passing of fines are important processes. The presence of mica flakes, on the other hand, indicates possible deposition, or that winnowing and/or by-passing are not being carried out efficiently (Doyle *et al*, 1957). The mica in the Hawaz Sandstone ranges from traces up to 3%, locally 6%, and it occurs as elongate grains under the SEM (Figs. 5 & 6). Muscovite is easily identified by its platy nature and parallel extinction. It is colorless in plane-polarized light and shows bright second-order colors under-crossed polars. Muscovite is distinguished by its tabular appearance bent through compaction between quartz grains.

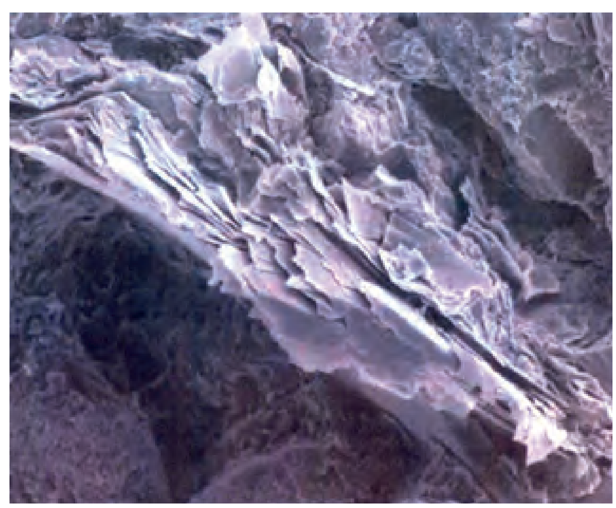

Fig. 5. SEM –photo: shows an elongate mica in the Hawaz Sandstone.

Clay Minerals: Clay minerals are the most common mineral group in sedimentary rocks, totaling about 45% by weight or volume. They are very small particles, commonly less than 1mm in size. The major clay minerals are kaolinite, montmorillonite, and illite. Nearly all clay-bearing sedimentary rocks contain more than one type of clay mineral (Blatt, 1982). The major origin of clay minerals is as subaerial weathering products of silicate minerals. All the chief clay groups are found in weathered residues and

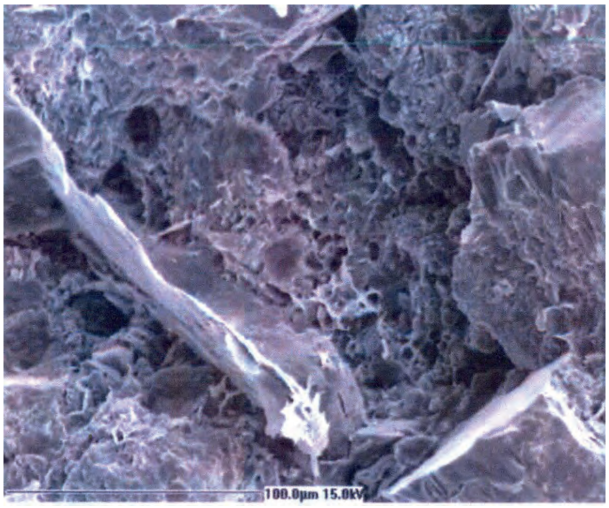

Fig. 6. SEM –photo: showing sheets of mica within the Hawaz Sandstone.

soils. Humid climates and well-drained topographies lead to extensive weathering of feldspars and their silicates to kaolinite. Lower rainfall and poorer drainage may result in the formation of smectite from the same parent materials. Mafic silicates in many climates will go to smectite. Illite products may form in intermediate to humid climates (Pettijohn *et al*, 1987). The clay minerals in the Hawaz sandstones are dominated by kaolinite (Fig. 7), which is colorless in plane-polarized light and grey-dark grey in cross polarized light, with weak birefringence.

Other Constituents

Pyrite: The mineral pyrite is a common and widespread authigenic constituent of sediments and sedimentary rocks where it is almost always found associated with organic matter. FeS_2 forms from aqueous solution only in the presence of elemental sulphur or substances that produce elemental sulphur during decompaction (Berner, 1970). Several types of pyrite are present, with some having provenance significance whereas, others are post-depositional in origin (Gavinil *et al*, 2002). Pyrite is most common in marine sandstones because of the availability of the sulphate in seawater, but it is only an accessory diagenetic mineral. Pyrite is commonly altered to goethite/limonite on surface weathering (Tucker, 1981). Pyrite crystals in the Hawaz Formation range from traces up to 1%. Although the cubic pyrite grains are authigenic rather than detrital, they show the typical yellow-gold metallic color of pyrite in reflected light.

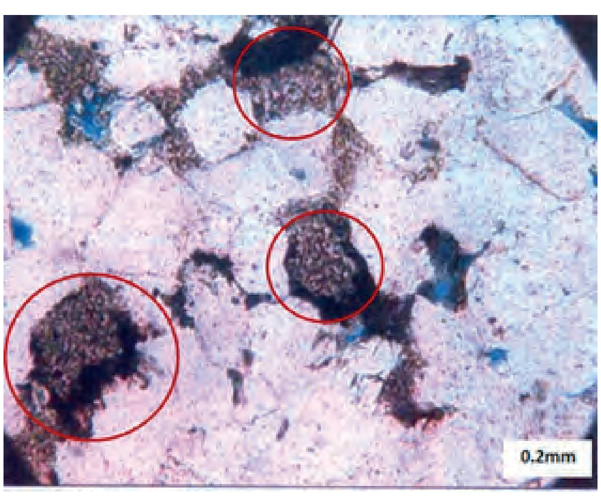

Fig. 7. Photomicrograph showing kaolinite replaced detrital grains and kaolinite fill pores in the Hawaz Sandstone, PPL, X20.

Sandstone Maturity

A distinction may be drawn between mineralogical maturity, which is strongly influenced by the composition of the source rock area, and textural maturity, which is more related to the history of transport and deposition (Nichols, 1999). Typically, compositionally immature sediments are located close to their source area, or they have been rapidly transported and deposited with little reworking from a source area of limited physical and chemical weathering (Tucker, 2001). It is widely believed that sorting is best when sand is repeatedly exposed to reworking by currents of moderate intensity. Probably the worst sorting occurs in sands subject to one brief episode of mass transport, such as a submarine slide, which is deposited below wave base in deep water (Pettijohn *et al*, 1987). Folk in (1951) described four stages of textural maturity. (1) Immature stage in which the sediment contains considerable clay and fine mica, the non-clay portion is itself poorly sorted, and the grains are angular. (2) Sub-mature stage in which the sediment contains very little or no clay, but the non-clay portion is still itself poorly sorted and the grains are angular. (3) Mature stage in which the sediment contains no clay and is well-sorted, but the grains are still subangular. (4) Super-mature stage. The framework grains in the Hawaz Sandstone are subrounded to subangular well sorted to moderately well sorted and texturally mature (Fig. 8 and Nichols, 1999).

Classification of the Hawaz Sandstone

A full description of sandstones usually includes some information concerning the types of grain present. Informal names such as 'micaceous sandstone' are used when the rock clearly contains a significant amount of a distinctive mineral, in this case mica (Nichols, 1999). There are several

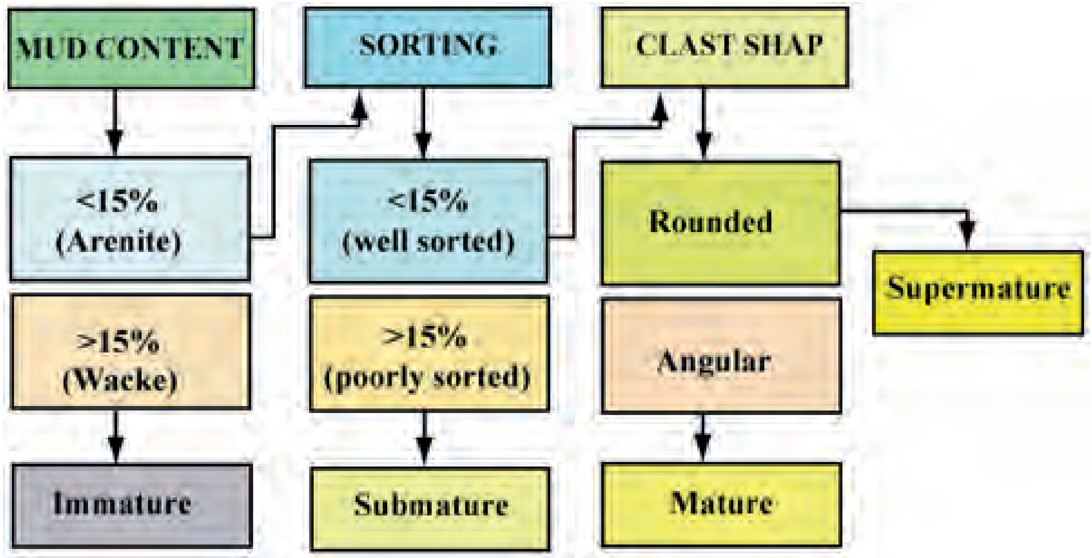

Fig. 8. Flow diagram for the determination of the textural maturity of a terrigenous clastic sediment or sedimentary rock (Nichols, 1999).

classification schemes available and most use a triangular diagram with end members of quartz (Q), feldspar (F) and rock fragments (L). The triangle is divided into various fields, and rocks with an appropriate modal analysis are given a particular name (Tucker, 1981). A widely used simple classification of sandstones is presented by Pettijohn *et al* (1987) based on the origin of the sandstone. The classification distinguishes between the "clean" sands or arenite-sands with less than 15% matrix and the "dirty" sands or wackes with more than 15% matrix (Pettijohn *et al*, 1987). The sandstones of the Hawaz Formation are classified according to that as mainly arenites, quartz-rich but feldspar and rock fragment poor (Fig. 9). The percentage of quartz in the Hawaz sandstones ranges between 96 to 99%, relative to feldspar and rock fragments, and the quartz is dominated by monocrystalline grains with abundant polycrystalline grains.

Many quartz arenites originate as shallow marine (but above storm wave base) sands that accumulated along or near the shoreline as beach, shoreline dune, tidal flat, spit, barrier island, or longshore bar deposits (Prothero and Fred, 1996).

Provenance of the Hawaz Sandstone

The term provenance, derived from the French "provenir", meaning to originate or to come forth, has been used to encompass all the factors relating to the production or "birth" of the sediment (Pettijohn *et al*, 1987). Sand composition, which is initially a function of the breakdown of a particular parent rock type under a given set of climate-induced weathering conditions, is subject to later modification during transportation, deposition, and diagenesis (Suttner *et al*, 1981).

In many cases quartz arenites are the products of extended periods of sediment reworking, so that almost all grains other than quartz have been broken down by mechanical abrasion. Climate in the source area can also play a major role in producing quartz arenites. A warm humid climate will lead to the removal of many unstable grains, and if this is coupled with low relief and slow sedimentation rates, quartz will dominate the detritus. Many quartz grains in these arenites could be second cycle, derived from preexisting sediments (Tucker, 1981). Ternary diagrams have been used to plot the Hawaz Sandstone composition data for J4-NC186 (Fig. 10). These indicate that they were derived from similar parent rocks, under humid climatic conditions from plutonic and metamorphic rocks. According to Suttner *et al* (1981) humid weathering raises the proportion.

Diagenesis

Diagenesis has been divided into two broad stages: early diagenesis, for processes taking place from deposition and into the shallow-burial realm, and late diagenesis for those processes affecting the sediments at deeper levels, and on uplift. The terms eogenesis, mesogenesis and telogenesis have been used for early and burial diagenesis and diagenesis-on-uplift, respectively (Tucker, 2001).

From the microscope observations various diagenetic features can be recognized in the Hawaz

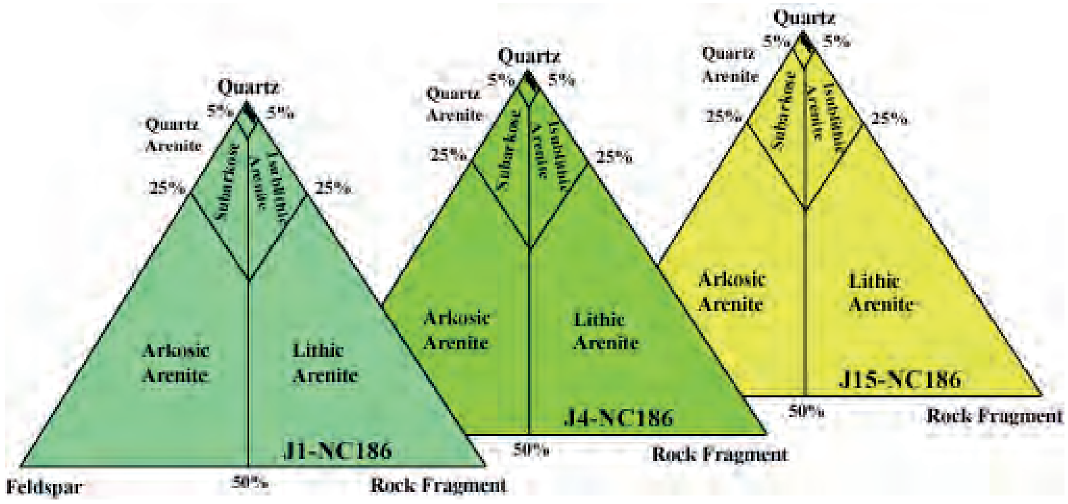

Fig. 9. Detrital composition of the Hawaz sandstones J4-NC186; A1-NC186, and H27-NC115, plotted in on a Pettijohn *et al* (1987) classification diagram.

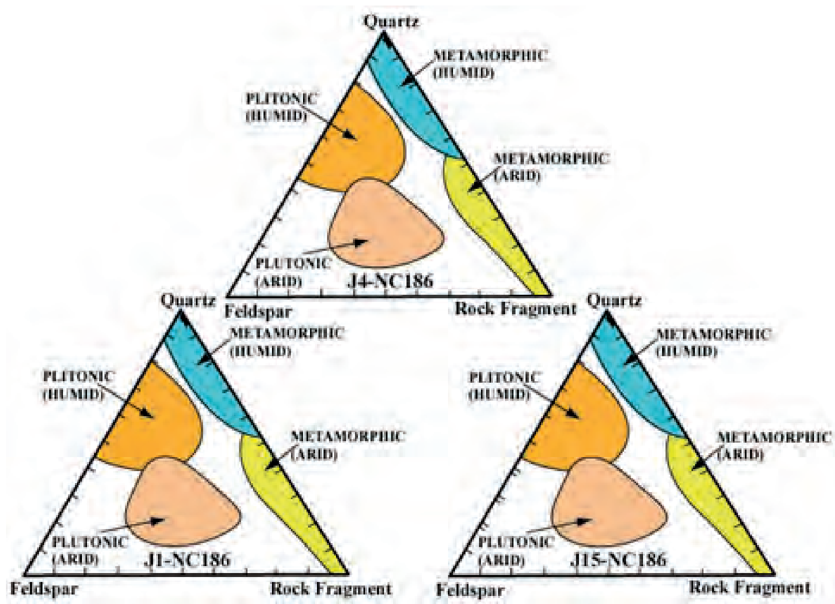

Fig. 10. Ternary QFRF plot showing the average composition of sandstones and source rocks for J4-NC186, which fall within the metamorphic humid climate field, (Suttner *et al*, 1981).

Formation including quartz overgrowth, calcite cement, chemical compaction (including pressure dissolution of minerals) and kaolinite and pyrite cement (Fig. 11).

Quartz Overgrowth: Quartz is the most common silicate mineral that acts as a cement in most sandstones, the quartz cement is chemically attached to the crystal lattice of existing quartz grains, forming rims of cement called overgrowths. Overgrowths can be recognized by a line of impurities or bubbles that mark the surface of the original grain. Quartz overgrowths are particularly common in quartz-rich sandstones (Boggs, 1995). The quartz overgrowth is the first diagenetic precipitate and characterizes early burial (Siever *et al*, 1962), but it can occur at any time in the diagenetic sequence (Hancock and Taylor, 1978).

From thin sections analysis and SEM studies, it can be demonstrated that the deposition of quartz overgrowths occurred at an early diagenetic stage and continued to grow periodically throughout burial diagenesis, as evidenced by preservation of primary intergranular volume. The early quartz overgrowths can be seen under the microscope by a dust rim but good crystal terminations are scarce or absent (Figs. 12 & 13). The quartz grains are medium to very fine-grained, subrounded to

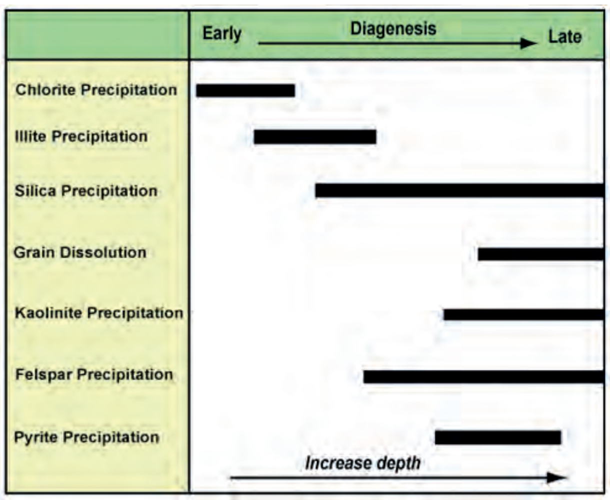

Fig. 11. Paragenetic sequence of diagenetic events in the Hawaz Sandstone, J1-NC186; J4-NCI86 and H15-NC186.

subangular, well-sorted to moderately well-sorted, and near symmetrically skewed.

Carbonate Cementation: The most common diagenetic phase in sandstone (up to 30%) is carbonate cements in the form of calcite and dolomite, which rarely coexist in one sample. Dolomite occurs chiefly as a sparry interstitial cement or more rarely as a replacement of detrital plagioclase or as a fracture fill. The bulk of the calcite and dolomite is interpreted to be a relatively early cement, because when abundant within a rock, associated detrital micas are compacted (Boles, 1982).

Calcite is one of the most common cements in sandstones, but other carbonate cements of more local importance are dolomite and

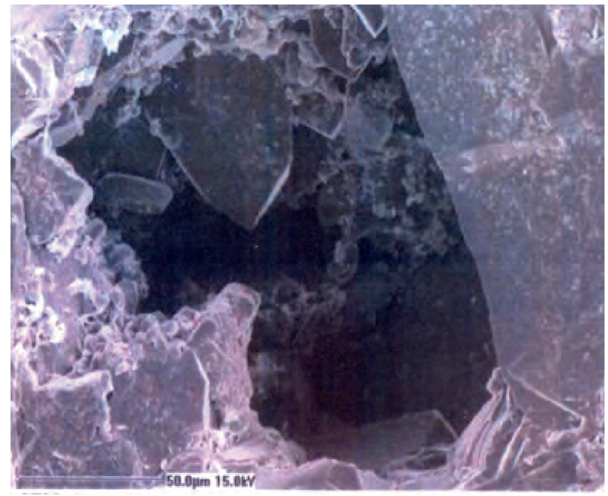

Fig. 13. SEM Photomicrography, showing quartz overgrowth with good crystal face. Note the quartz grain surface shows small features (wisps) which may be an indication that the grains were carried out by floating ice to the place where it was deposited.

siderite. The cement may vary from a uniform to patchy distribution, to local segregations and concretions. The two main types of calcite cement are poikilotopic crystals and drusy calcite spar (Tucker, 1981). Carbonate cementation is favoured by increasing concentration of calcium carbonate in pore waters and increasing burial temperature (Boggs, 1995). They take several forms. In most cases each individual pore is filled by a single crystal of calcite, whilst in others, the calcite crystallized in large "poikilitic" patches which enclose many sand grains (Pettijon *et al*, 1987). Carbonate cementation in the Hawaz Formation (J4-NC186; A1-NC186 and J15-NC186) is volumetrically minor and dominated by calcite. The calcite occurs

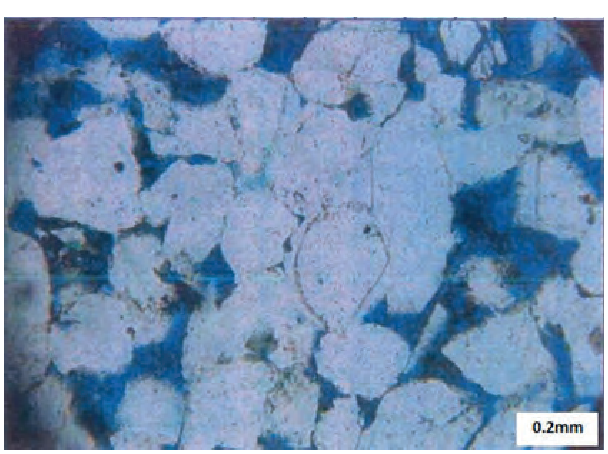

Fig. 12. Photomicrograph showing quartz overgrowths, PPL, (X20), in the studied wells.

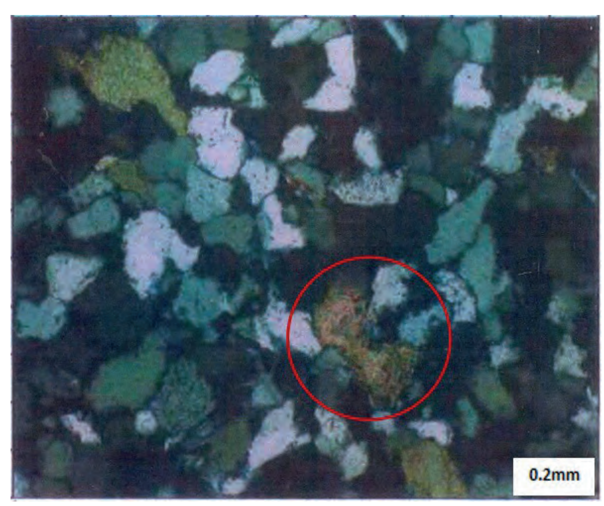

Fig. 14. Photomicrograph, showing pore-filling calcite cement within the Hawaz Sandstone, XPL, (Xl0).

both as isolated patches between grains as a grain-support, and as pore-filling (Fig. 14). The calcite causes corrosion of the margins of quartz grains. The calcite can be interpreted as an early cement which has been dissolved and the space probably filled by authigenic and kaolinite.

Dissolution of Unstable Grains: The potassium feldspars show petrographic evidence of alteration (Fig. 15) which can also be recognized under the SEM (Fig. 16). Most K-feldspar grains appear quite fresh or slightly broken whereas, the microcline and plagioclase encountered have been affected by dissolution. The microcline feldspar can be recognized by its grid twining. Late-stage quartz overgrowths can be distinguished by the quartz filling the pore space on one side, destroying the porosity, and being surrounded by crystals on the other sides (Figs. 15 & 16).

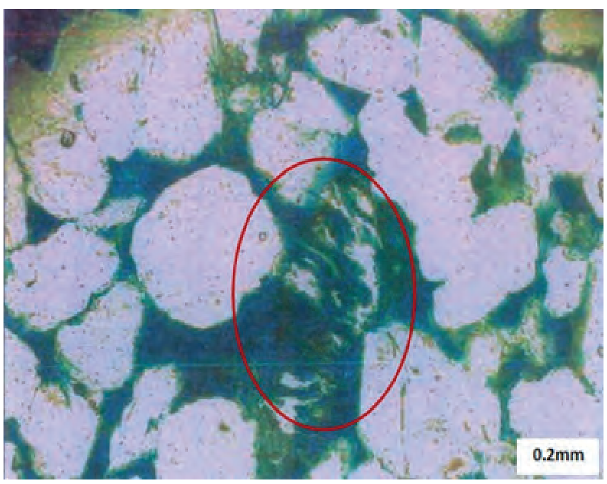

Fig. 15. Photomicrograph, shows the dissolution of an unstable feldspar grain in the Hawaz Sandstone, PPL, (Xl0).

Authegenic Clay Minerals: Clay minerals in sandstones may be both detrital and authigenic. Detrital clay mineral types cannot be identified with the petrological microscope, but some authigenic clays can. All the chief clay-mineral groups are represented in sandstones: kaolinite, illite, chlorite, smectite and mixed-layer clay. Detrital clays reflect the source-area geology, climate and weathering processes (Tucker, 2001).

Authegenic Kaolinite: The authegenic clay minerals in the Hawaz Sandstone are dominated by kaolinite. It partly fills both primary and secondary porosity. Secondary porosity probably formed from feldspar crystals which

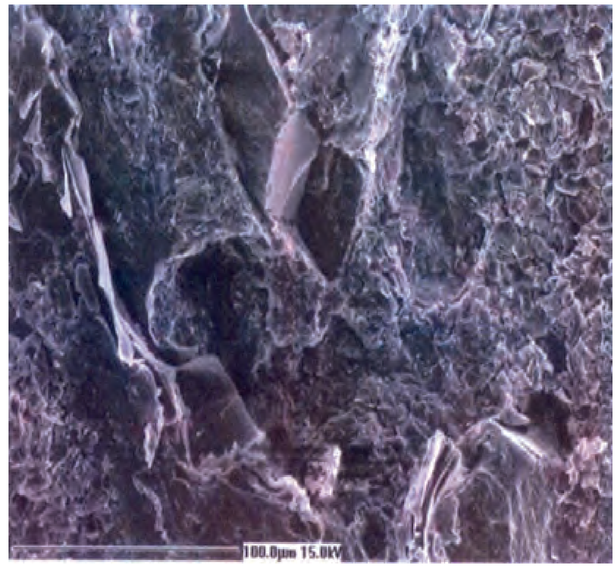

Fig. 16. SEM Photomicrography, shows the dissolution in the feldspars,

were subsequently dissolved, leaving a residue of kaolinite clay (Scholle and Schluger, 1979), showing well developed pseudo-hexagonal basal plates in curved vermicular stacks, (Fig. 17).

Authegenic Illite and Chlorite: Other clay minerals present in the Hawaz Formation sediments are smectite, illite and chlorite, which are present in amounts ranging from traces to up to 1%. The smectite under the SEM (Fig. 18) shows irregular, wavy plates or sheets. Illite forms needle-shaped crystals with strong birefringence, but it has not been recognized in the selected SEM samples. Chlorite is precipitated from pore fluids in rare patches on detrital grains, and from rock weathering and alteration of ferromagnesian minerals, such as biotite.

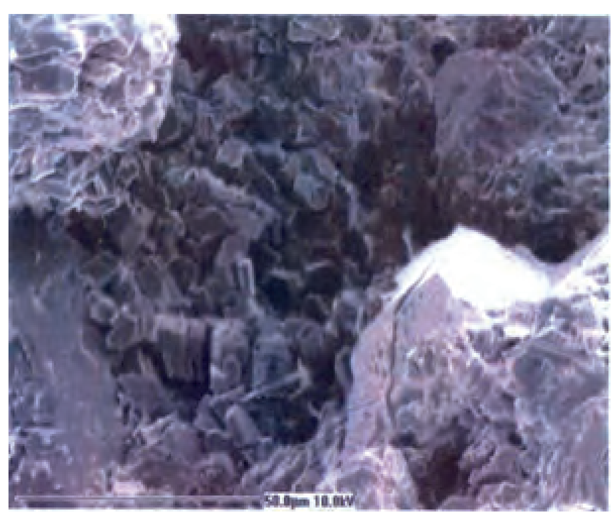

Fig. 17. SEM photomicrography shows pore-filling, book-shape plates of kaolinites.

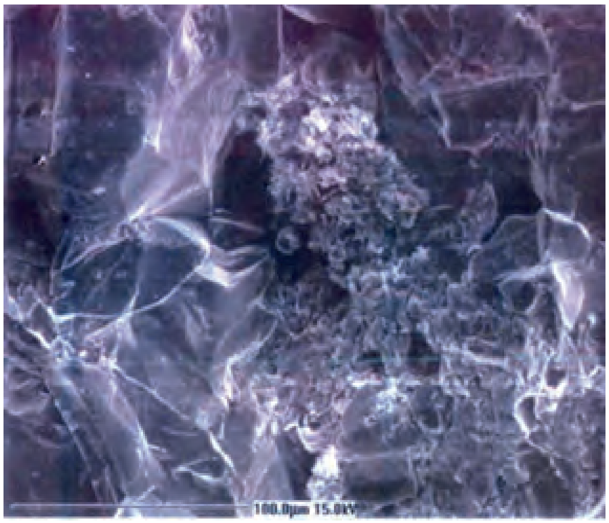

Fig. 18. SEM Photomicrography, showing the smectite within the Hawaz Sandstone.

CONCLUSIONS

This study of the Hawaz Sandstone shows that:
Hawaz Formation consists predominantly of alternating fine to medium-grained, well-sorted to moderately well-sorted sandstone displaying a variable degree of bioturbation.

- The Hawaz Formation was deposited in wave-dominated shoreface and shelf environments. The stratigraphical and sedimentological characteristics of the Hawaz Formation in the study area in the Murzuq Basin are attributed to shoreface and shelf facies associations within which some 9 facies have been distinguished. The lower part of the cored section of the Hawaz Formation is dominated by the outer and inner shelf facies associations.
- The outer shelf association is dominated by mudstone whereas, the inner shelf association is dominated by siltstone/sandstone.
- Petrographic data shows that the Hawaz sandstones can be classified mainly as a quartz arenite, with local subarkoses.
- Diagenetic cement is mainly in the form of quartz overgrowths, and local calcite and clay matrix, all of which have reduced the porosity.

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