JKAU: Earth Sci., **vol. 10,** pp. 45-57 (1419 A.H. / 1998 A.D.)

Petrography and Diagenetic Controls on Reservoir Characteristics in Unayzah Formation, Central Saudi Arabia

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Received: 15th June, 1996 Accepted: 10th March, 1997

ABSTRACT. The Unayzah Formation forms the basal part of the Permo-Carboniferous sedimentary succession in central Saudi Arabia and represents a transgressive and regressive unit, comprised of sandstone and shale/claystone sequences situated above the thick Qusaiba Shale (Silurian) and below the Khuff Carbonate (Permian). The sandstones are fine to medium grained and the majority of the samples are moderately well sorted quartzarenite. The upper and lower parts of the formation differ in the intensity of their diagenetic changes as well as in their detrital mineralogy and this is probably due to different provenance. Mechanical compaction due to depth in the range of 9500-11800 feet reduces the porosity to an average of 25%. Ductile grains played an important role during compaction as a result of high porosity loss by mechanical compaction. Silica grains in the form of overgrowth also reduced porosity to some extent. Important diagenetic changes took place during maturation of the underlying Qusaiba Shale and expulsion of acidic and organic solutions transported into the overlying Unayzah Formation to enhance the development of secondary porosity in the quartz-rich sediments. The humid and tropical climate and several transgressive and regressive cycles resulting in deep weathering and reworking were also responsible for destruction of unstable minerals which lead to increase in porosity. The study has its economic importance because of the recent discovery of hydrocarbons in the same formation in wells drilled in the eastern and southeastern parts of the Arabian basin.

Introduction

Central Saudi Arabia shows the effects of "Hercynian" tectonism on Devonian to Permian sediments (Saint-Mark, 1978). The main "Hercynian" event occurred during the Carboniferous. The results of this event are reflected in regional uplift and a new peneplanation that cut across the newly formed platform, eroding as deep as the Precambrian (Murris, 1980). This was followed by a major transgression of the sea over the whole region and deposition of a comparatively thin succession of almost flat lying siliciclastic strata of Late Carboniferous-Early Permian age. This siliciclastic unit of sandstone and thin beds of siltstone and claystone was previously referred to the Unayzah member which forms the basal part of the Permian Khuff Formation (Powers *et al.* 1966; Delfour *et al.* 1982). Later it was upgraded as the Unayzah Formation by Al-Laboun (1987) and a reference section was designated in the Qusaiba area in Al Qassim region, Saudi Arabia. In this region the formation fills a north-trending narrow trough bounded on the east by the Summan platform and on the west by the Arabian Shield (Al-Laboun 1987). The present author studied the reference section of the Unayzah Formation east of the Qusaiba depression (Lat. 26º54′48″ N. Long. 43º34′40″ E.) which comprises sandstones and claystone and is conformably overlain by massive carbonates of the Khuff Formation, and its basal contact unconformably overlies the various older sedimentary units (Fig. 1). The Unayzah Formation is dominated by medium to fine grained, cross bedded quartzarenite with subordinate claystone and siltstone (Fig. 2). These sequences were mainly deposited by a series of marine transgressions and regressions (Al-Laboun 1987). On the basis of several plant fossils El-Khayal *et al.* (1980) assigned them a Late Carboniferous-Early Permian age.

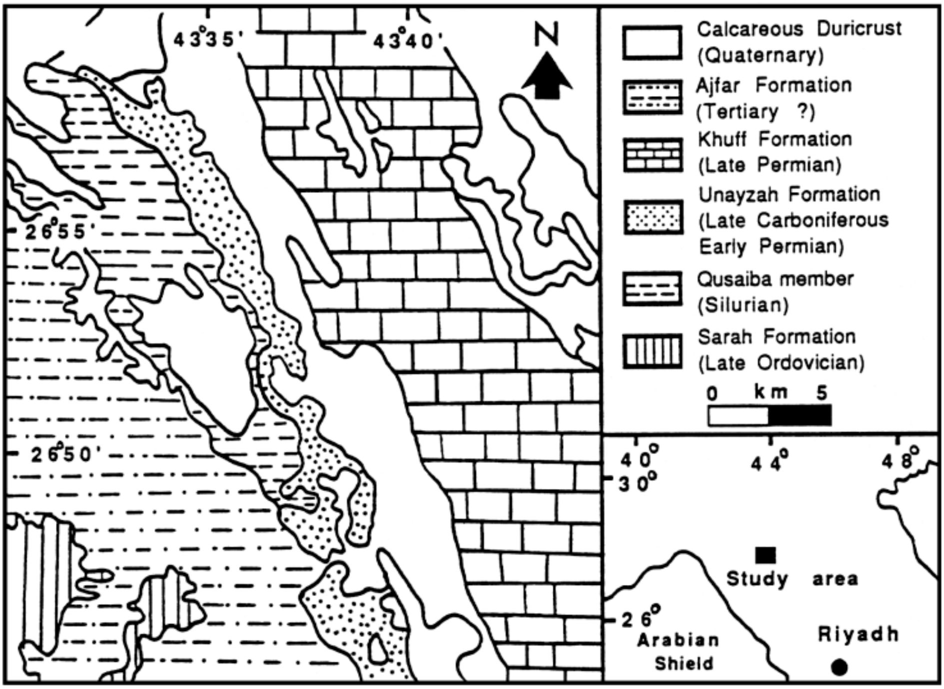

FIG. 1. Geological map of the Unayzah Formation, central Saudi Arabia (after Manivit *et al.* 1986).

The objective of this study is the understanding through petrographic study, of the effects of diagenesis on the reservoir characteristics of the sandstones.

The study was mainly carried out using detailed thin section petrography and X-ray Diffraction (XRD) of fresh samples collected from outcrops.

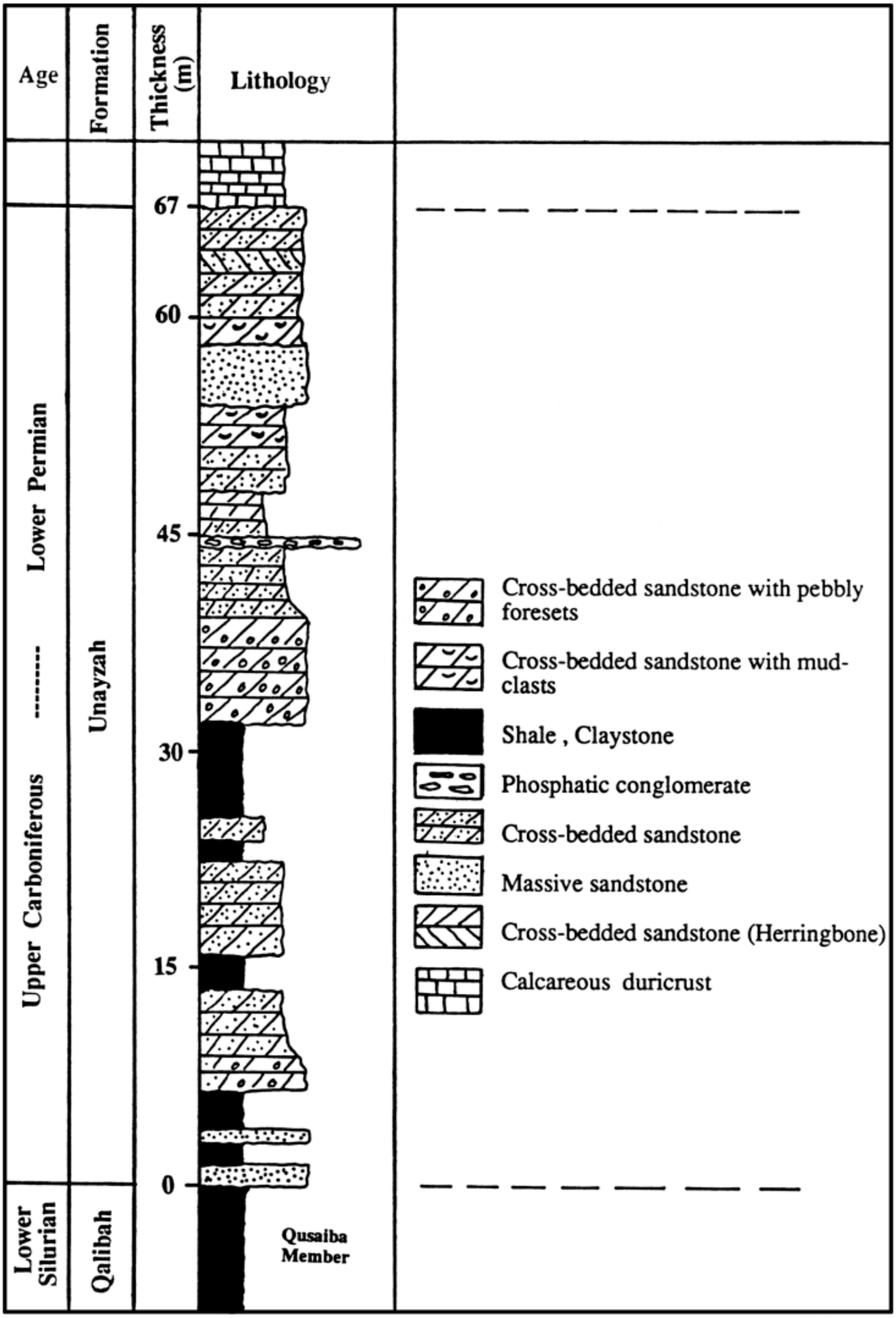

FIG. 2. Lithostratigraphic section measured east of Qusaiba depression.

Sandstone Composition and Texture

The Unayzah Formation is composed of fine to medium grained sandstones which show little vertical variation with a slight fining-upward trend. The majority of samples are moderately well sorted (65%) and the grains are subangular to subrounded. On the average, the sandstone is composed of 85% detrital grains, 4% void spaces and 11% cements. The detrital grains are composed on average of 95% quartz, 3% feldspar 1% rock fragments and trace amounts of mica and heavy minerals.

The cements include 2% silica, 4% iron oxide, 2% carbonate and 3% authigenic clay. The minus cement porosity (void space and cement) defined by Rosenfeld (1949) and Heald (1956) ranges from 8 to 28% and averages 15%.

Grain contacts of the sandstone were also studied in thin sections with a view to interpret their compaction history. The ranges of percentages of the various types of grain contacts in the sandstone are: floating grains, 2 to 46% and average 18%; point contact, 6 to 63% and average 31%; long contact, 5 to 90% and average 51%; sutured and concave/convex contacts are rarely observed.

Depth of Burial and Textural Controls on Compaction

When the average minus cement values (15%) of the Unayzah sandstone were plotted on graphs, it suggested a depth of burial ranging from 9500-11800 feet was obtained (Fig. 3) (McCulloh, 1967; Lapinskaya and Proshlyakov, 1970; Selley, 1978; Dixon and Kirkland, 1985; and Wilson and McBridge, 1988). At the time of deposition, the original porosity of the sandstones has been assumed to be 40% (Beard and Weyl, 1973; Manus and Coogan, 1974; and Sibley and Blatt, 1976). In the case of the Unayzah Formation, the minus cement porosity average (15%) is less than the assumed original porosity of 40%. This difference is a measure of porosity reduction mainly due to compaction.

The relationship of grain-size to sandstone composition was studied by plotting mean size versus percentages of quartz and feldspar. There is no significant correlation between the mean size and quartz content. However, a statistically positive correlation was obtained between feldspar and mean size which indicates that the feldspar is concentrated generally in the finer-grained fractions.

Cementation

Four types of cements were identified in the Unayzah sandstone and their paragenesis was determined, in the order of their formation (Fig. 4).

The silica cement is seen in the form of overgrowths. However, identification is difficult due to their optical continuity with the detrital grains. In some grains overgrowths are clearly identified from the detrital grains which possess a thin coating of brown limonite material. A few overgrowths are quite large and occur as pyramidal and prismatic growth showing sharp and planar crystal faces. The percentage of silica cement ranges from 1 to 6% and averaging 2%.

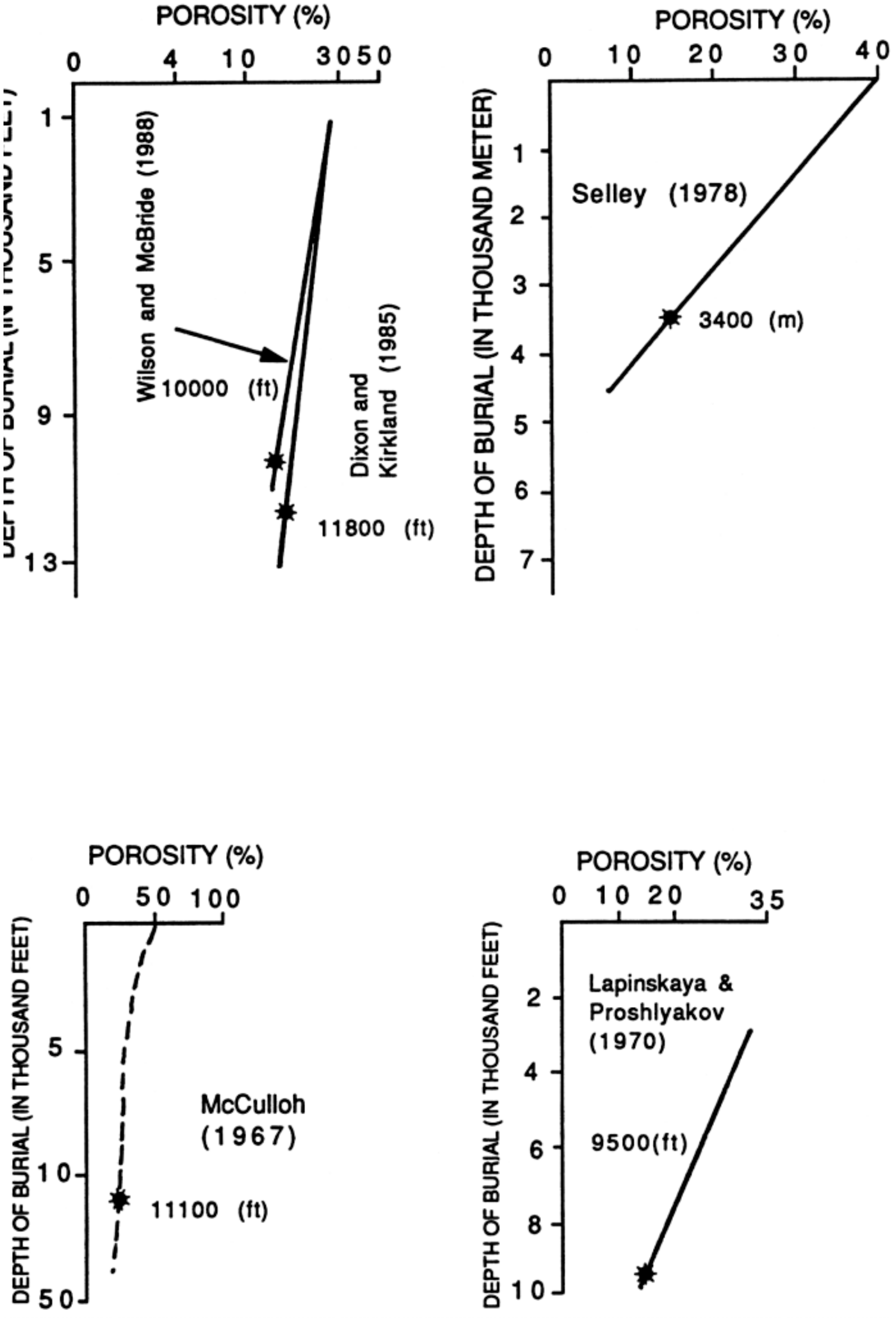

FIG. 3. Different graphs (Based on depth vs. minus cement porosity).

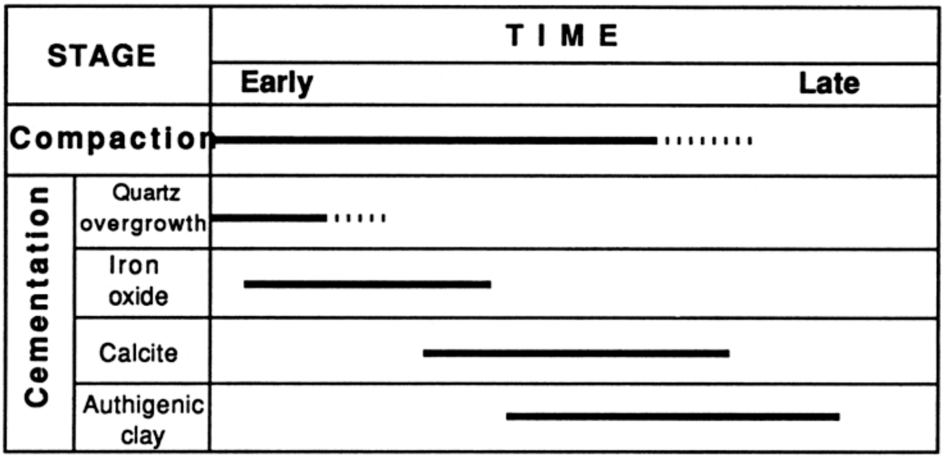

FIG. 4. Diagrammatic model showing different stages of diagenesis of the Unayzah Formation.

Iron oxide cement occurs in the form of dark brown coating on the detrital quartz. Similar coating also occurs around altered and leached feldspar grains. Empty voids, lined with a thin coating of iron oxide, have also been noted. These voids represent completely leached feldspars which have disappeared leaving behind pore spaces. Iron oxide cement ranges from 1 to 14% with an average of 4%.

In many samples carbonate cement occurs as both pore-filling and grain replacing calcite. The quartz grains have been subjected to dissolution and replacement by calcite cement. This process is evidenced by several features such as etching, pits, embayment and partial replacement of detrital grains; carbonate cement ranges from 1 to 8% and averages 2%.

Clay cement occurs as replacement of detrital feldspar and sometimes forms patches within the calcite cement. It is often stained with reddish brown limonite. Kaolinite is the most abundant among the clay minerals as shown in X-ray diffractograms (Fig. 5). It is very common in secondary pores replacing feldspar and mica, were remnants of feldspar are seen with kaolinite in some samples (Fig. 6a). The authigenic clay cement ranges from 1 to 7% with an average of 3%.

Discussion and Interpretation

Petrographic evidences show that the ductile grains occur in a very small quantity (1%) in the Unayzah sandstone, but their percentage was probably larger at the time of deposition. The sandstones are fine to medium grained. All the ductile grains are mechanically deformed at a very shallow depth of burial leading to the reduction of the porosity and permeability (Hamlin *et al.,* 1996). The grain size variation is of minor effect on the porosity of the sandstone.

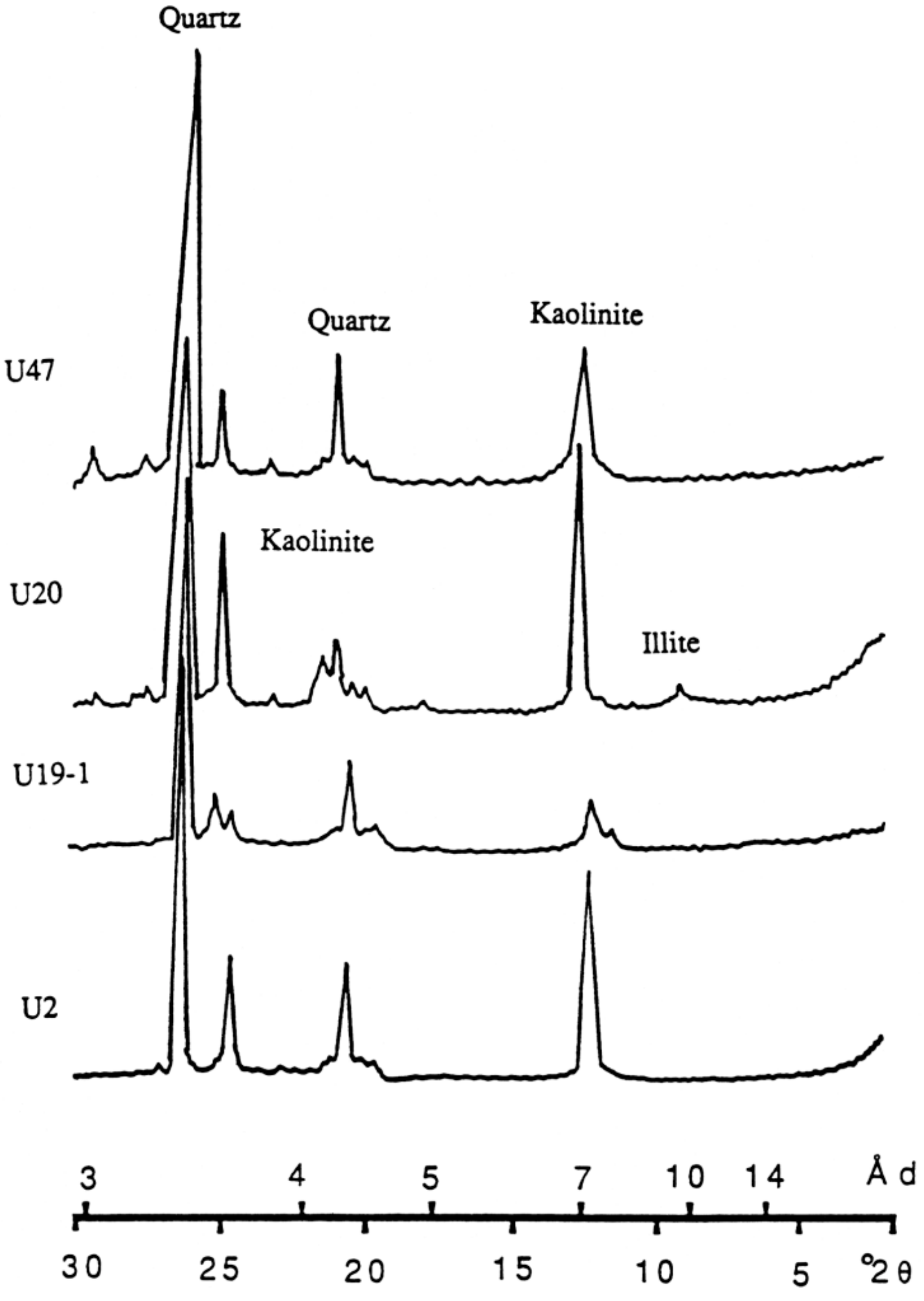

FIG. 5. X-Ray diffraction patterns of clayey samples from Unayzah Formation.

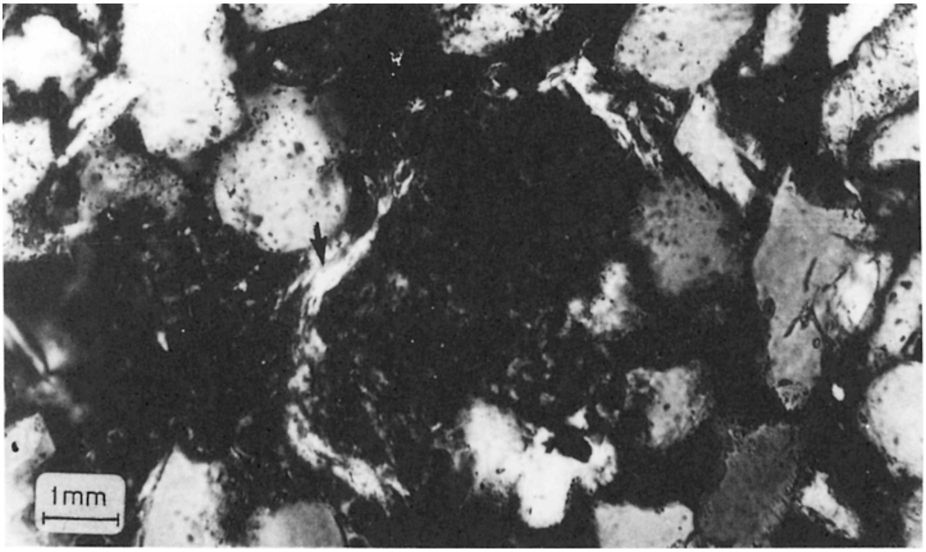

FIG. 6a. Photomicrograph showing remnants of feldspar with kaolinite (arrow).

The high percentage of floating grains in some samples is the result of corrosion of detrital grains and modification of texture by the carbonate cement. In some other samples which do not have carbonate cement, the corroded nature of grains indicates the earlier presence of carbonate cement and its subsequent removal by dissolution (Fig. 6b). Long contacts developed in a very early stage of compaction of the sediments are rotated and adjusted their boundaries with adjacent grains as a response to overburden pressure. Thus, long contacts represent an intermediate evolutionary stage between the original contacts and the final sutured contacts. The point and long contacts together average 82% and indicate that the sandstone was not subjected to much pressure solution, due either to shallow burial or early cementation (Fig. 6c).

Silica cement is interpreted to have precipitated, relatively early, in the form of overgrowths and partially in primary pore spaces. It is an important feature which controls the reservoir quality of the Unayzah sandstone. Reservoir quality destruction by silica cement is permanent because it is less affected by chemical weathering and mechanical reworking as compared to other cements. Fuchtbauer (1983) listed many possible sources of silica cement. They are: (a) dissolution of quartz grains in associated siltstone; (b) replacement of feldspar and quartz, (c) pressure solution; (d) alteration of smectite to illite; (e) volcanic sources; (f) compaction water from associated shales. In the studied sandstone, possible sources for forming overgrowths were either silica derived from the underlying Qusaiba shales by alteration of smectite to illite (Aktas and Cocker 1994), or dissolution of feldspar and mica grains. Land and Dutton (1978) also suggested that shale bodies underlying sand are the major source of quartz cement.

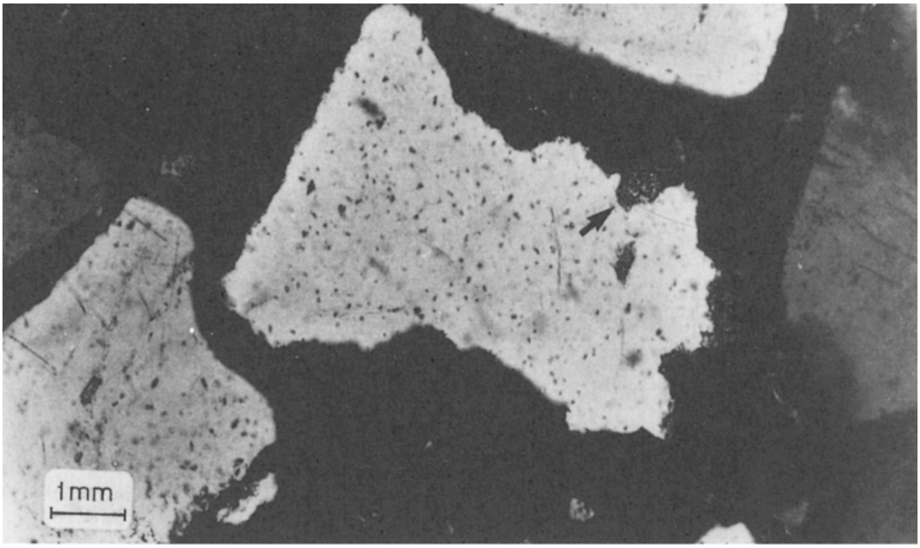

FIG. 6b. Photomicrograph showing corroded detrital grains and modification of texture by carbonate cement (arrow).

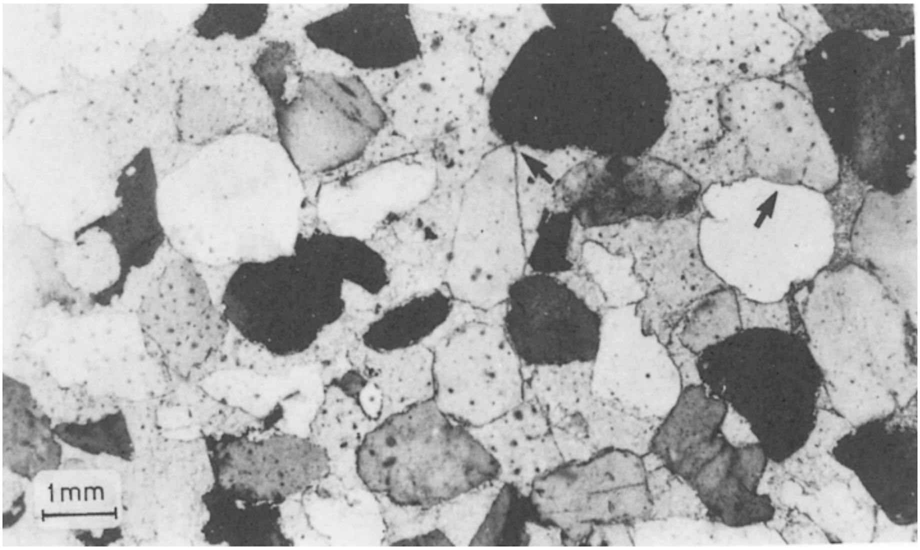

FIG. 6c. Photomicrograph showing point and long contact between quartz grains (arrows).

The lack of quartz overgrowths on some samples and relatively higher minus cement porosity suggest an early stage of carbonate cementation. Two probable sources of carbonate cements are suggested: (1) maturation of Qusaiba shale resulting in smectite to illite conversion and the release of Ca into solution to form carbonate cements, (2) the overlying Khuff carbonates also provide carbonate cements to the underlying Unayzah Formation. These cements were subjected to decementation and reprecipitation by the acidic and organic solutions of the Qusaiba Shale.

The feldspar percentage was greater at the time of deposition. Some feldspar was lost by dissolution, and the remnants of feldspar can be seen in some thin sections. It is also indicated by one sample of fine grained sandstone having more than 10% feldspar. The intense dissolution of feldspar and other ductile minerals has taken place at the contact of the Qusaiba shale with the overlying Unayzah sandstone. The Qusaiba shale solutions being acidic and organic in nature may have dissolved skeletal carbonates from the shales, and also penetrated in to the overyling sandstone. These solutions first removed the reactive feldspar and after that affected the calcite cement and provided the favorable conditions for the secondary porosity enhancement (Milliken and Land 1991). After the dissolution stage, kaolinite was precipitated as a cement and as a replacement product of the feldspar and micas (Fig. 6d). This process would be similar to that reported in the Green River Basin, Wyoming by Dutton (1993).

Petrographic investigation of Unayzah Formation showed that its lower part is devoid of feldspars (except one sample) and contains lesser amounts of calcite cements as compared with the upper part of the formation, which has a higher percentage of feldspar and calcite cements. It is mentioned earlier that the quartzose nature of the sediments in

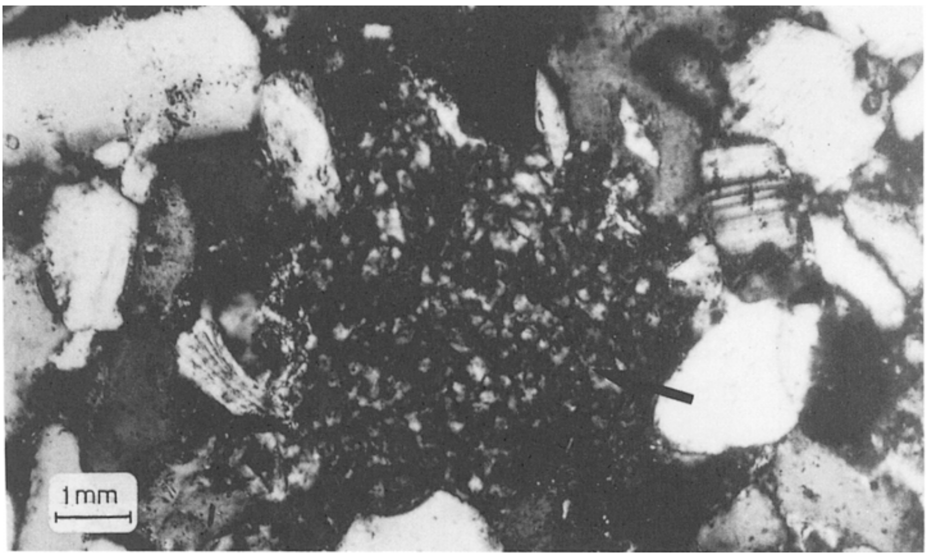

FIG. 6d. Photomicrograph showing kaolinite as an alteration and replacement product of feldspar (arrow).

the lower part is mainly due to the acidic and organic nature of the Qusaiba Shale solutions. Higher feldspar content in the upper part of the formation indicates that only small amounts of Qusaiba Shale solutions reached and mixed with older trapped meteoric water resulting in the dilution of solutions which were not capable of removing all the feldspar and other cements. The low permeability of fine grained sediments also prevents free circulation of acidic solutions and meteoric water, preventing feldspar dissolution. Different sources of sediments also provided higher percentages of feldspar. This is also indicated by different paleocurrent directions in the upper part of the formation. Al-Laboun (1987) also suggested that the shield area to the west was not the only source of sediments and that it could have been derived from rocks of different ages.

Generally, porosity and permeability decrease with depth through compaction and cementation, but in this study the trend seems to be reversed due to the dissolution of both grains and cements. The humid and tropical climate of the area at the time of deposition and several transgressive and regressive events, the resulting weathering and reworking, were also responsible for destruction of unstable minerals which increase porosity, and lead to mineralogically mature sediments.

Conclusion

The Unayzah sandstone is a mineralogically mature quartzarenite in which deformation of ductile grains played a significant role in compaction. The decrease of original porosity by 25% is mainly due to mechanical compaction, rearrangement of grains, and effect of pressure solution. The silica cement in the form of quartz overgrowths also reduced porosity though to a lesser extent. The important diagenetic event took place when the underlying Qusaiba shale, during its maturation and expulsion of acidic and organic solutions, transported these to the overlying Unayzah sandstone. Reservoir development of the Unayzah sandstone was controlled by a series of porosity-reducing and porosity-enhancing events. Trends in reservoir quality in the sandstone, defined by grain compaction, diagenesis by large volumes of organic solutions and depth of burial are indicators of potential hydrocarbon concentrations.

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تأثيـر التركيب الصخري وعمليات النشأة المتأخرة على خواص خزان متكون عنيزة وسط المملكة العربية السعودية

عمر الحربي
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المستخلص . يمثل متكون عنيزة الجزء السفلي من رواسب عصر البيرمي - الكربوني في وسط المملكة العربية السعودية . وهو وحدة ترسيبية تكونت من تقدم وانحسار البحر . ويتكون من حجر رملي وطفل ، وينحصر بين طفل القصيبة (عصر السليوري) من الأسفل ومتكون الخف (عصر البيرمي) من الأعلى . وتتراوح حجم حبيبات الحجر الرملي من ناعم إلى خشن وذو تصنيف جيد . إن اختلاف الجزء العلوي عن السفلي من متكون عنيزة ، من حيث تأثير عمليات النشأة المتأخرة وأيضًا من حيث المحتوى المعدني قد يرجع أساسًا إلى اختلاف مصدر الرواسب . ويرجع نقصان المسامية في صخور متكون عنيزة بنسبة ٢٥٪ إلى عملية الدمج الميكانيكي الواقعة على عمق يتراوح مابين ٩٥٠٠-١١٨٠٠ قدم . وتلعب الحبيبات اللينة دوراً هامًا في الدمج الميكانيكي حيث تعمل بدورها على نقصان المسامية ، كما يعمل النمو الثانوي لحبيبات المرو على نقصان المسامية . وتظهر أهمية عمليات النشأة المتأخرة عند نضج طفل القصيبة حيث تطرد المحاليل العضوية والحمضية إلى متكون عنيزة وبذلك تتكون المسامية الثانوية ورواسب ناضجة . ويعزي زيادة المسامية وتحلل المعادن الغير ثابتة في متكون عنيزة إلى المناخ الاستوائي الرطب السائد أثناء عملية الترسيب . وتقدم وإنحسار البحر ، والتجوية ، وأيضًا إلى عمليات إعادة الترسيب . وتظهر الأهمية الاقتصادية لهذه الدراسة من خلال الاكتشافات البترولية الجديدة في شرق وجنوب شرق الحوض العربي .