

## **Mineralogy and Geochemistry of Unayzah Formation, Central Saudi Arabia: Implications for Provenance Interpretation**

**Omar A. Al-Harbi and M. Mujtaba Khan**

*Natural Resources & Environment Research Institute,  
King Abdulaziz City for Science and Technology, Riyadh, Saudi Arabia  
P. O. Box 6086 Riyadh 11442, Saudi Arabia*

(Received 2/3/1423H.; accepted for publication 30/5/1425H.)

**Abstract.** The Unayzah Formation (Permian-Carboniferous), a thick sedimentary succession of clastic unit deposited after the Hercynian orogeny in central Saudi Arabia. Transgression and regression as a result of eustatic change deposited these sediments. Unayzah formation consists of sandstone and shale. The provenance of the formation has been identified by petrographic and geochemical methods. On the basis of petrography, the formation can be divided into a feldspar-free lower unit, and a feldspar-bearing upper unit. The petrographic data suggest that the sediments are derived from craton interior (82.5%) and are of recycled origin (17.5%). However, the data mainly supports intense reworking during the course of deposition rather than recycling; chemical weathering in the source area and postdepositional change (diagenesis) are responsible for mature quartzarenite. The geochemistry of sandstone and shale indicate that the tectonic settings of the study areas were passive margin and polycyclic continental fields. Finally, the petrographic, chemical and paleocurrent data indicate that the probable provenance of the sediments were the Arabian Shield to the west, and some other sources.

### **Introduction**

The Unayzah Formation (Permian-Carboniferous) covers most of the Arabian basin [1]. These rocks are also well developed in different parts of the Middle East, with different names as the Al-Khalta and Gharif Formations of the Haushi Group of Oman [2]. Most of the workers differ in Unayzah Formation as far as thickness is concerned. Earlier workers such as Aley & Nash [3] and Laboun [1] measured a section in Qusaiba depression 35 and 34m; Senalp and Duaji, [4] 36.3m; and even the BRGM people like Manivit *et al.* [5] measured the section 60m. The work of Daniel *et al.* [6] proved that the area has different thickness due to the undulated nature of paleochannel in Qusaiba depression. This is the first clastic unit, deposited immediately after the Hercynian tectonic events, which created the tectonism in the central region of Arabian plate by regional and local tilting, and reverse faulting in Upper Carboniferous and Permian times. This tectonism uplifted and

exposed broad area to erosion. The Unayzah Formation (Permian-Carboniferous) which underlies the Khuff Formation is composed of sandstone, siltstone and mudstone [1]. According to Husseini [7], it was the result of epeirogenic movements and broad uplift in the North Gondwana region in Late Paleozoic time.

The study area lies east of Qusaiba depression in Qassim district ( $26^{\circ} 55' 27''$  N.,  $43^{\circ} 34' 37''$  E.), (Fig. 1). The clastic unit (Unayzah Formation) is underlain by the organic-rich Qusaiba Shale member and is overlain by calcareous duricrust of Quaternary age. These are the result of transgression and regression [1]. This locality is considered the thickest outcrop section of the Unayzah Formation. On the basis of several mega floras, El-Khayal and Wagner [8] suggest a warm, humid climate in the area at that time of deposition of Unayzah sediment. Petrographical studies of sedimentary rocks have long been used in interpretation of the provenance source [9-12]. The composition of sandstone is also affected by factors other than tectonic setting, including paleoclimate [13-15], reworking and transport history [16-19] and diagenesis [20]. Geochemical analyses are also helpful in the interpretation of the provenance and tectonic setting of the source rocks [21-24].

In the present study the petrographic and geochemical data are integrated for the interpretation of provenance of Unayzah sediments. The integrated approach provides information regarding the lithology, chemical composition and sedimentation history of the source rocks.

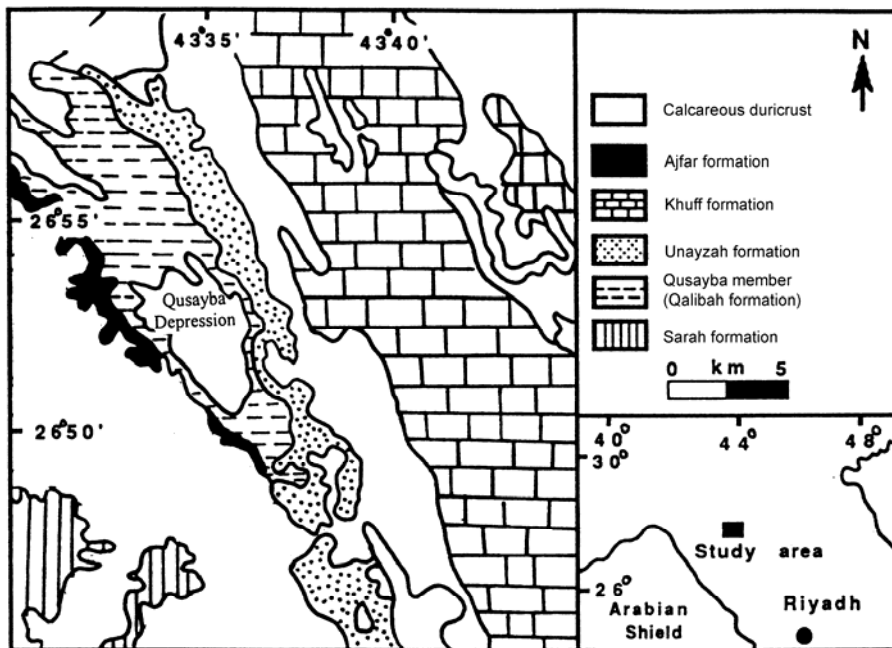


Fig. 1. Location and simplified geological map of Unayzah Formation (after Manivit *et al.*, 1986).

### Methodology

In the present study, the detrital mineral composition of sandstone was evaluated in 20 thin-sections. For quantitative analysis, 300 grains were counted in each. Staining with sodium cobaltinitrite solution identified k-feldspar grains. Twenty-three representative sandstone and shale samples were chosen for chemical analysis.

### Sandstone Composition and Tectonic Setting

All of the sandstones from the Unayzah Formation have quartzarenite composition. Quartz forms 98% by the volume of the total detrital minerals in the sediments of Unayzah Formation samples collected. The grains are medium to fine in size, moderately well sorted to well sorted and subrounded to rounded. The quartz grains are dominantly monocrystalline (98% of total quartz grains) and most of them quartz show non-undulose extinction (80% of the total monocrystalline quartz grains), but 18% have slightly undulose extinction. The percentage of grains with undulatory extinction is relatively high in the coarser sizes. Fine-grained sandstones have a much smaller percentage of either polycrystalline or undulose quartz grains. The polycrystalline quartz is present in a small amount (1.5% of total quartz grains) and is of two types: recrystallized metamorphic quartz and stretched metamorphic quartz. The subindividual grains boundaries of recrystallized metamorphic quartz (39% of the total polycrystalline quartz) are equidimensional with straight contacts and different optic orientation, whereas stretched metamorphic quartz grains (61% of the total polycrystalline quartz) have elongated crenulated or sutured boundaries. Quartz grains show highly undulose extinction. Some of the polycrystalline quartz has more than three subindividual grains (23.5% of the total polycrystalline quartz) and few have less than three grains (76.5% of the total polycrystalline quartz).

The majority of the feldspar is K-feldspar (71%) and the remainder is plagioclase. The most of the plagioclase feldspar is altered (68% of the total plagioclase feldspar) and the remaining is less altered. Most of the K-feldspar is fresh (62% of the total K-feldspar). Paucity of rock fragments and heavy minerals are noted in this mineralogically mature quartzarenite. However, ultrastable heavy minerals such as opaques, zircon, rutile and tourmaline are characteristic features in some of the studied samples. Grain parameters and recalculated parameters used in this study are those of Dickinson's scheme [10]. Two standard triangular diagrams Qt-F-L and Qm-F-Lt were employed, where:

$$Qt = Qm + Qp$$

Qt = total quartzose grains  
 Qm = monocrystalline quartz grains  
 Qp = polycrystalline quartz grains

$$F = P + K$$

F = total feldspar grains  
 P = plagioclase feldspar grains  
 K = potassium feldspar grains

$L = L_v + L_s$        $L$  = total unstable lithic fragments  
                           $L_v$  = volcanic/metavolcanic lithic fragments  
                           $L_s$  = sedimentary/metasedimentary lithic fragments  
  
 $L_t = L + Q_p$        $L_t$  = total lithic grains  
                           $L$  = total unstable lithic grains  
                           $Q_p$  = polycrystalline quartz.

The detrital modes of Qt-F-L and Qm-F-Lt composition of 20 point counted thin sections fall within the craton interior (82.5%) and recycled origin (17.5%) fields of Dickinson and Suczek [5], and Dickinson's [6], provenance diagrams (Fig. 2). Most of the studied samples are quartzarenite according to McBride's classification scheme [25].

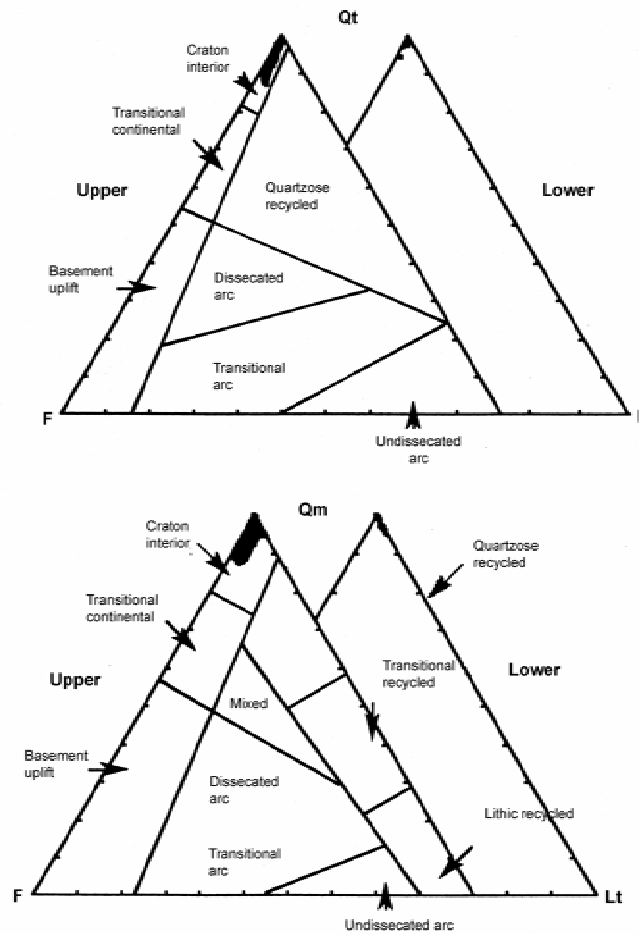


Fig. 2. Distribution of detrital models of Unayzah Formation in the provenance diagrams of Dickinson (1985).

### Geochemistry, Tectonic Setting and Palaeoclimate of the Provenance

Only the major elements in sandstone and shale/claystone of the Unayzah Formation were analyzed (Table 1). The results were used in the interpretation of provenance, tectonic setting and impact on diagenesis.

The studied sandstones are enriched in SiO<sub>2</sub> (91%), and have low contents of Al<sub>2</sub>O<sub>3</sub> (2.8%), CaO (2.26%), Fe<sub>2</sub>O<sub>3</sub> (1.02%) and TiO<sub>2</sub> (0.13%). The shales are also dominated by SiO<sub>2</sub> (66.2%), followed by Al<sub>2</sub>O<sub>3</sub> (12.0%), Fe<sub>2</sub>O<sub>3</sub> (3.19%), CaO (6.0%) and TiO<sub>2</sub> (0.20%).

A number of major oxide-based diagrams were employed by Bhatia [21, 26], Roser and Korsch [23, 27]) to determine tectonic setting have been applied to Unayzah sandstones.

On the FI vs. FII plot (Fig. 3) of Roser and Korsch [27], all the studied samples, fall within the polycyclic continental sedimentary field. According to Bhatia's [21] discriminant function (Fig. 4), most of the studied samples (80%) fall within the field of passive margins and the remaining (20%) fall into that of active continental margins. Using Roser and Korsch's [23] method for volatile free elements, the variation of K<sub>2</sub>O/Na<sub>2</sub>O vs. SiO<sub>2</sub> diagram (Fig. 5) shows that all the majority of the studied samples (93%) fall into the passive margin field and the remainder (7%) into that of an active continental margin.

Nesbit and Young [28] have given a formula to calculate the chemical index of alteration (CIA) in shale, as  $100 \frac{Al_2O_3}{Al_2O_3 + CaO + Na_2O + K_2O}$  for intensity of chemical weathering in the source area. Eriksson *et al.* [29] also used this formula in the interpretation of sandstone. In their opinion, sandstone is also susceptible to weathering like shales. The results for the Unayzah Formation rocks show variation of alteration between shales (39.01%) and sandstone (39.08%) (Fig. 6). It indicates that sandstone in the area is slightly more altered as compared to shale.

### Discussion and Interpretation

The presence of about 18 percent of monocrySTALLINE quartz with straight to slightly undulose extinction may indicate plutonic source but other sources can also produce this type of quartz [30]. MonocrySTALLINE quartz with inclusions of acicular rutile, may be derived from both igneous and metamorphic rock sources [31]. Undulose quartz is considered fewer stables and easily breaks into small grains. Many authors believed that undulatory quartz is the result of folding and faulting of the sandstone [32, 33]. Based on quartz typology Wahab, [34] suggests that undulosity of quartz grains is not related to parent rock, but is a result of postdepositional tectonic strain phenomena. The presence of recrystallized metamorphic quartz is related to a metamorphic origin and is formed where quartz-bearing rocks such as sandstone are strained without recrystallization [10].

Table 1. Chemical analysis (major elements) of the Unayzah Formation

Sample No.	U18	U19	U20	U21	U22	U23	U25U26	U28	U29	U31	U33
	(shale)	(shale)	(shale)	(shale)							
SiO <sub>2</sub> (%)	90.14	59.42	71.15	56.04	84.50	92.36	92.88	88.28	93.78	92.46	81.25
Al <sub>2</sub> O <sub>3</sub>	3.740	12.850	9.250	14.10	1.840	2.890	1.480	1.740	3.170	2.300	6.400
Fe <sub>2</sub> O <sub>3</sub>	0.800	1.250	6.590	1.740	0.390	0.500	0.800	0.188	0.330	1.200	4.880
MnO	0.005	0.003	0.010	0.005	0.002	0.004	0.003	0.002	0.003	0.002	0.007
MgO	0.520	0.630	0.198	0.587	0.070	0.066	0.940	0.80	0.030	1.960	0.980
CaO	0.810	7.460	5.846	4.507	8.510	2.480	1.440	4.920	1.618	0.216	2.175
Na <sub>2</sub> O	0.120	2.850	0.070	3.950	0.030	0.110	0.080	0.020	0.20	0.020	0.060
K <sub>2</sub> O	0.027	0.185	0.158	0.300	0.251	0.018	0.070	0.121	0.221	0.180	0.413
TiO <sub>2</sub>	0.186	0.194	0.193	0.201	0.172	0.152	0.117	0.060	0.146	0.124	0.170
H <sub>2</sub> O+	1.760	10.43	4.590	11.700	2.950	1.320	0.690	4.060	0.780	1.190	2.860
H <sub>2</sub> O-	0.520	4.890	0.620	5.350	0.120	0.150	0.160	0.090	0.140	0.100	0.280
<b>Total</b>	<b>98.628</b>	<b>100.162</b>	<b>98.775</b>	<b>98.530</b>	<b>98.835</b>	<b>100.050</b>	<b>98.660</b>	<b>99.561</b>	<b>100.238</b>	<b>99.752</b>	<b>99.474</b>

Table 1. (Continued)

Sample No.	U34	U35	U37	U38	U40	U42	U44	U45	U47	U49	U51
SiO <sub>2</sub> (%)	89.76	90.17	91.35	88.18	87.90	93.29	93.40	92.27	91.77	93.81	93.80
Al <sub>2</sub> O <sub>3</sub>	4.220	2.230	2.280	4.710	4.340	1.860	2.260	1.420	1.760	2.630	1.900
Fe <sub>2</sub> O <sub>3</sub>	0.446	1.400	2.350	0.300	0.890	0.170	0.360	2.840	1.580	0.390	0.260
MnO	0.001	0.002	0.001	0.003	0.006	0.002	0.002	0.006	0.001	0.002	0.001
MgO	0.030	0.030	0.018	0.040	0.047	0.139	0.067	0.139	0.060	0.19	0.040
CaO	2.662	3.340	0.887	2.590	1.980	3.030	1.340	1.330	4.150	2.980	2.001
Na <sub>2</sub> O	0.000	0.020	0.003	0.090	0.900	0.050	0.050	0.060	0.020	0.20	0.030
K <sub>2</sub> O	2.115	0.090	0.070	2.062	1.839	0.425	0.405	0.366	0.214	0.168	0.229
TiO <sub>2</sub>	0.056	0.130	0.110	0.162	0.182	0.117	0.112	0.159	0.077	0.123	0.093
H <sub>2</sub> O+	1.470	1.440	0.940	1.550	1.860	0.540	0.810	1.540	1.240	0.710	0.830
H <sub>2</sub> O-	0.130	0.110	0.100	0.150	0.190	0.100	0.090	0.090	0.090	0.060	0.080
<b>Total</b>	<b>100.890</b>	<b>98.962</b>	<b>98.109</b>	<b>99.837</b>	<b>100.134</b>	<b>99.723</b>	<b>98.896</b>	<b>100.220</b>	<b>100.972</b>	<b>100.912</b>	<b>99.255</b>

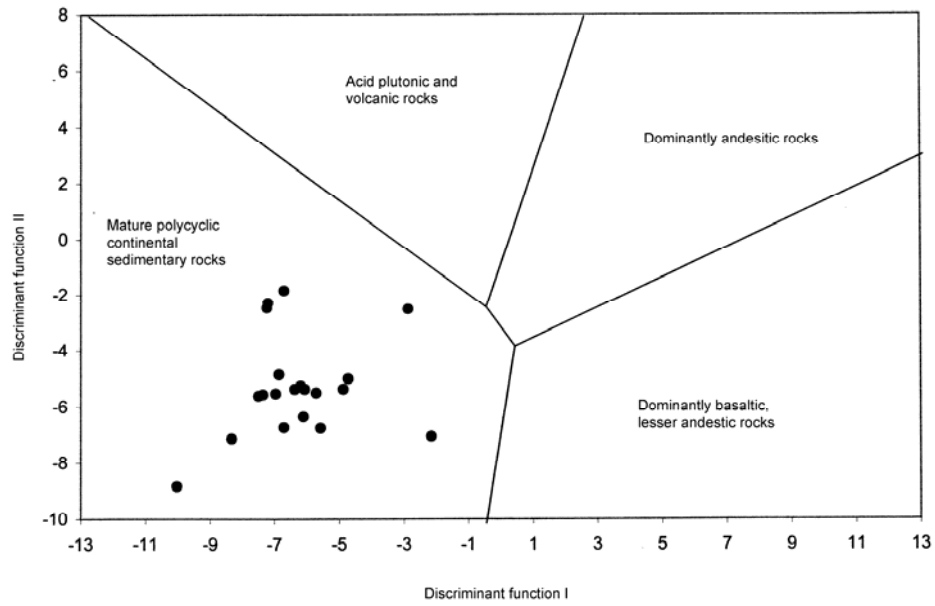


Fig. 3. Discriminant function analysis classification plot of function FI and function FII scores for the Unayzah Formation (after Roser and Korsch, 1988).

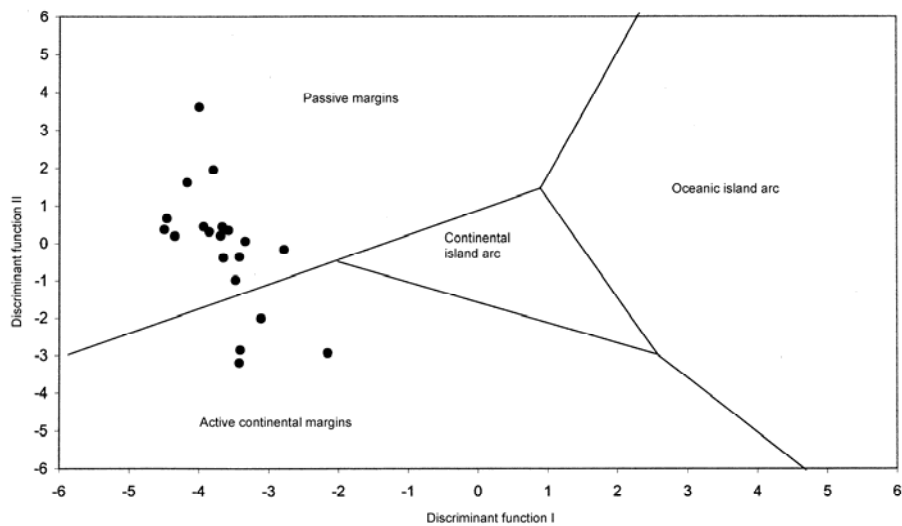


Fig. 4. Discriminant function analysis classification plot of function FI and function FII scores for the Unayzah Formation (after Bhatia, 1988).

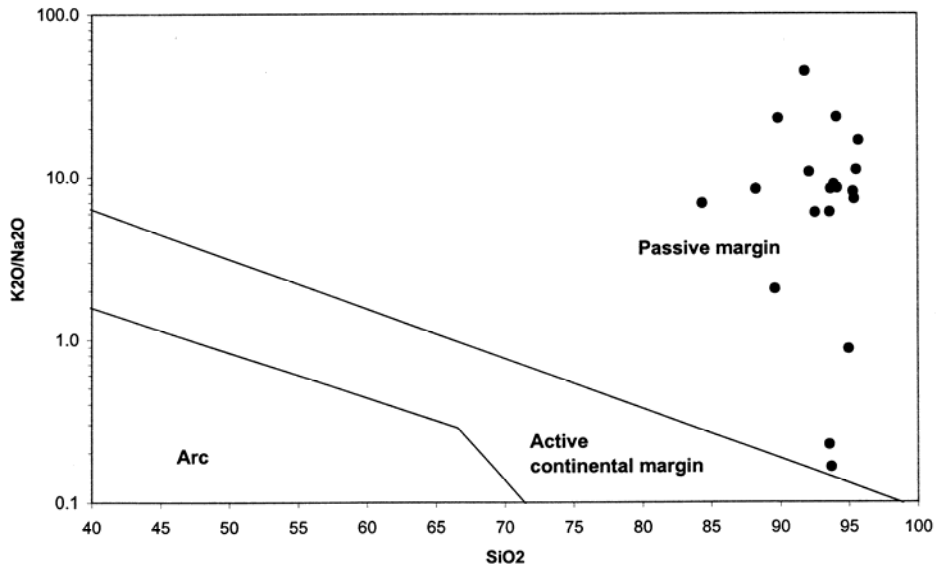


Fig. 5. Tectonic discrimination diagram for Unayzah Formation, 100% volatile free (after Roser and Korsch, 1986).

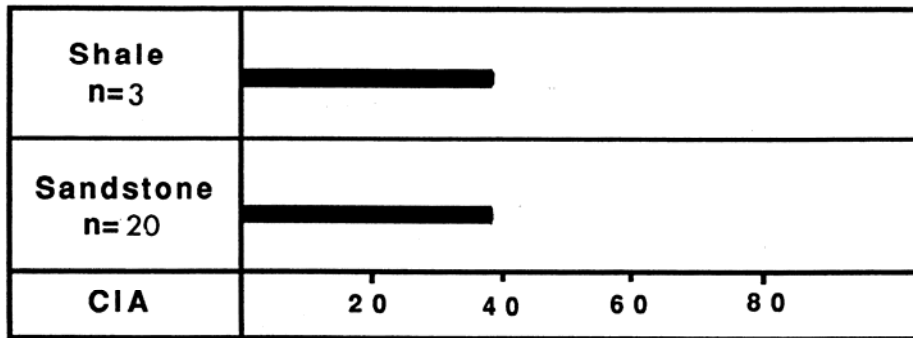


Fig. 6. Chemical index (CIA) of Unayzah sandstone and shale (after Nesbit and Young, 1982).

The sandstone under study, when plotted on standard triangular diagrams (Fig. 2), indicates craton interior provenance, because all samples fall in the craton interior field. Dickinson and Suczek [11] suggested that the sediments of continental block provenance are normally derived either from the stable shield platforms or from uplifted areas, and are inherited mainly from sedimentary strata and subordinate volcanics within the orogen.

Sandstone within a low percentage of polycrystalline quartz and feldspar, sorting is compositionally mature. Destruction of feldspar and sorting is due to reworking of the sediment, paleoclimate and diagenesis.

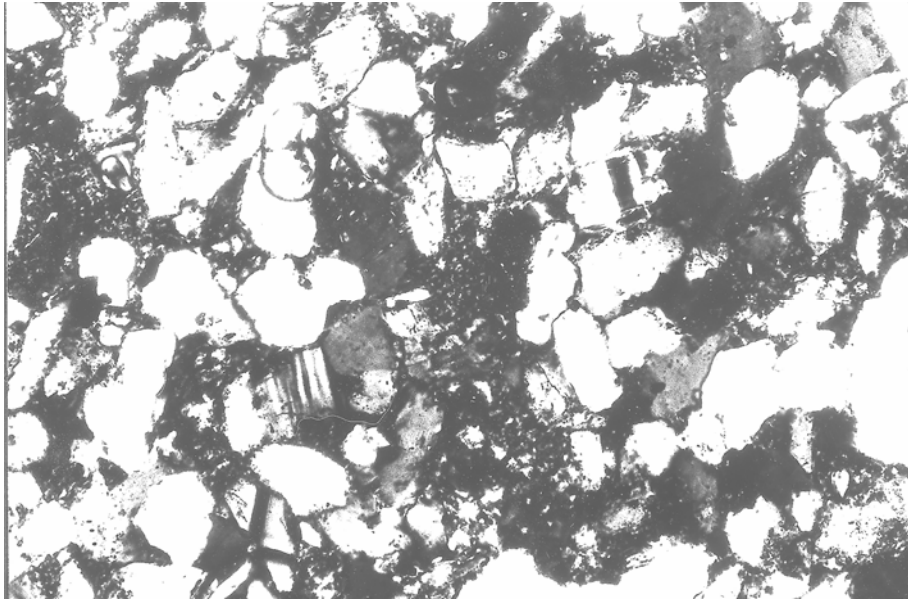
Unayzah sandstone was deposited by transgression and regression [1]. In this process a lot of reworking and winnowing of sediments took place, as evidenced by moderately well to well sorting, and subrounding to rounding of the constituents grains. In reworking, waves are more efficient than unidirectional currents because of their continuous action [17]. The predominance of fine to medium grains in the study sands are produced by reworking in a high-energy marine environment, which also correlates with Mack's views [35].

Swett *et al.* [12], in considering the role of reworking, calculated that a detrital grain in a tidal environment moves about 100 m/day in an oscillating path, and that in a million years, 36.5 x 10<sup>6</sup> km of total transport is possible. They also calculated 31.5 x 10<sup>6</sup> km/million years for wave dominated littoral environment. Schwab [36] suggested that only cratonic and passive continental margins have sedimentation rates low enough to allow sufficient reworking to produce first cycle quartzarenite. This can be applied to the Unayzah sandstones, which are shown to be of craton interior provenance (Fig. 2). The presence of high percentage of monocrystalline compared to polycrystalline quartz associated with a small amount of feldspar is due to reworking of the sediment.

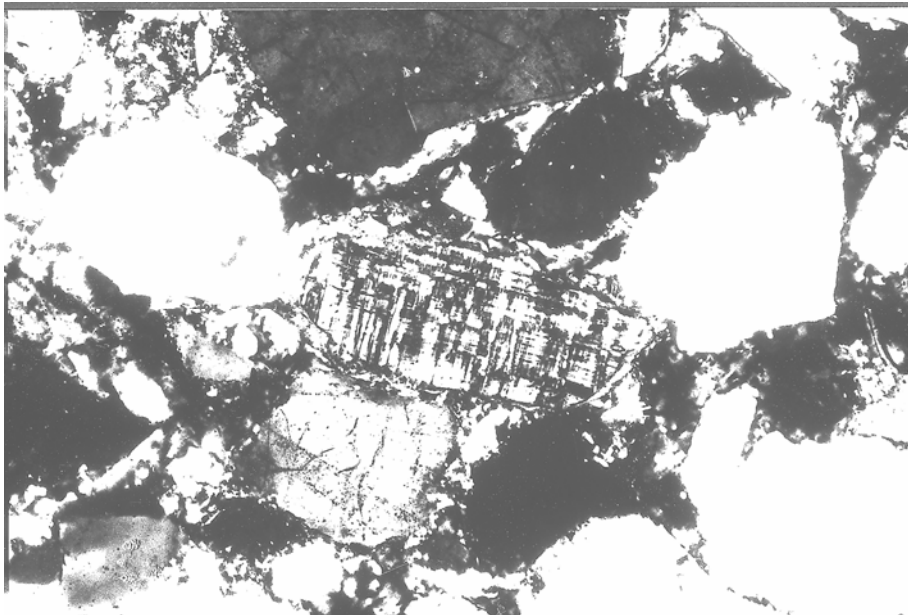
Meanwhile, palaeoclimate of the area has played an important role in producing quartz-rich sediments. The climate of the area was tropical to subtropical in late Paleozoic time [8]. This climate and low relief nature of the area produced chemical weathering, high enough to reach the alteration of feldspar. The presence of a small amount of feldspar in the upper part of the studied sandstone, along with the association of both altered and fresh feldspar indicates derivation from two different sources (Figs. 7 and 8). Al-Laboun [1] argued that the shield areas to the west were not the only source of sediments for the Unayzah Formation. His arguments are based on palaeocurrent trends and other sedimentary structures, especially in the upper part of the formation. The resulting sediments, in his opinion, could have been derived from rocks of various ages by reworking and deposition. Sandstone and shale geochemistry (CIA) indicates a very limited or absent chemical weathering [28].

The higher percentage of CaO content in samples (U19, U22) is due to carbonate cements. These are confirmed from petrographic studies. The low percentage of Na<sub>2</sub>O (0.37%) is due to the loss of plagioclase during alteration. The higher percentage of alumina in shale samples ranging from 2 to 15% is derived probably from granitic source rocks [37].

The discriminate plots of Roser and Korsch [27] as well as of Bhatia [21] show that the majority of samples (100%) and (80%) fall within the recycled continental sources, and passive margin field, respectively. This provenance is commonly interpreted as



**Fig. 7. Photomicrograph showing principal feldspar grain altered along the c cleavage (40X).**



**Fig. 8. Photomicrograph showing altered and fresh feldspar in fine to medium grained sandstone (20X).**

representing clastic compositions typical of passive continental margin, intracratonic sedimentary basins and recycled orogenic provinces. Nathan [38] and Bhatia [21] also suggested that these sediments were derived from a pre-existing sedimentary terrane or older adjacent continental terranes.

The most common parameters for tectonic setting discrimination are  $TiO_2$ ,  $Al_2O_3/SiO_2$ ,  $Al_2O_3 (CaO + Na_2O)$  and  $K_2O / Na_2O$  versus  $FeO_3 + MgO$  percentage plots of Bhatia [21]. None of the studied samples fall within the specific fields of Bhatia's. The lower part of the Unayzah Formation is contacted with the thick unit of Qusaiba Shale, which produces acidic and organic fluids [39]. These fluids entered into the overlying Unayzah sandstone and to react with feldspar and carbonate and produced mineralogically mature quartzarenite.

### Conclusion

The provenance of the studied samples was probably rich in quartz as the presence of pre-existing sandstone. The chemical results are also in favor of recycling of the sediment.

The petrography and most of the chemical results show that the sediments were derived from crystalline parent rocks of the Arabian Shield to the west, which consist of granites, low and high grade metamorphic rocks and pre-existing clastic sediments. The tectonic instability in the area can be one of the reasons for variation in detrital composition in the formation. Owing to limited sources available during these studies, the complexity of reworking and chemical weathering of the sediments could not be fully identified. The feldspars were also removed during diagenesis, especially in contact with the studied sandstone and Qusaiba Shale and shale within the formation as well. The presence of small amount of feldspar in the upper part of the formation is probably due to less reworking of fine sediments, little accessibility of acidic and organic-rich fluids from the Qusaiba shale units and the missing of shale beds within sandstone units. It is possible that originally these sediments were rich in feldspar and due to the reworking within shallow marine environments, climatic effects, and diagenesis; these sediments were changed to quartzarenite. A comparison of provenance knowledge with lithological studies correlates the former to the latter to some extent. Finally, based on petrography and lithostratigraphy, the Unayzah Formation can be subdivided into lower and upper units.

**Acknowledgement.** The author is grateful to the King Abdulaziz City for Science and Technology (KACST), for using their facilities.

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معهد بحوث الموارد الطبيعية والبيئة، مدينة الملك عبدالعزيز للعلوم والتقنية  
ص.ب. ٦٠٨٦، الرياض ١١٤٤٢، المملكة العربية السعودية

(قدم للنشر في ٢/٣/١٤٢٣هـ؛ وقبل للنشر في ٣٠/٥/١٤٢٥هـ)

. يعتبر متكوّن عنيزة ذو العمر الكربوني البيرمي أول وحدة ترسبية هيدروكربونية ترسبت بعد حركة هيرسيان البانية للجبال وترسبت بفعل تغير مستوى البحر من تقدم وانحسار ويتكون من أحجار رملية وطفل. استخدمت طرق التركيب المعدني والجيوكيميائي لتحديد مصدر الرواسب، حيث تم تقسيم المتكون إلى علوي وسفلي. ويدل التركيب المعدني للرواسب على أن مصدرها من دروع ذات نشاط تكتوني معدوم (٨٢.٥٪) ومن صخور رسوبية معاد ترسيبها (١٧.٥٪)، ويعزى نضوج هذه الرواسب إلى عمليات الترسيب والتعرية في حوض الترسيب والتجوية الكيميائية وكذلك إلى عمليات النشأة المتأخرة وليس إلى إعادة الترسيب. ويعتقد أن الدرع العربي ومصادر أخرى هي مصدر رواسب متكون عنيزة وذلك بناءً على نتائج التركيب المعدني والجيوكيميائي وقياسات اتجاه التيار في هذه الرواسب.