Revista
GEOCIÊNCIAS

unesp

ISSN: 1980-900X (online)

PETROLOGY AND GEOCHEMISTRY OF SANDSTONE FROM LOWER CRETACEOUS KIKHLA FORMATION, NW LIBYA: IMPLICATIONS FOR PROVENANCE AND DEPOSITIONAL SETTING

PETROLOGIA E GEOQUÍMICA DE ARENITOS DA FORMAÇÃO KIKHLA (CRETÁCEO INFERIOR), NW LIBYA: IMPLICAÇÕES PARA PROVENIÊNCIA E AMBIENTE DEPOSICIONAL

Ali S. BEN SERA

Department of Geology, Faculty of Sciences, University of Zintan, P.O.Box 718. Zintan, Libya. ORCID 0000-0003-3968-7009.
E-mail: a.bennasirh@uoz.edu.ly

RESUMO - Este estudo visa determinar e investigar a proveniência das rochas geradoras e o ambiente deposicional da Formação Kikhla, Cretáceo Inferior, noroeste da Líbia. É composta principalmente de arenito quartzítico maduro alternando com conglomerado e argila. O estudo reconheceu arenito com coloração amarelo-esbranquiçada e comumente carrega quartzo granular e pequenos fragmentos de madeira silicificada. A deposição ambiental ocorreu sob diferentes condições fluviais e por um grande rio entrelaçado. Texturalmente, o arenito Kikhla é mal cimentado, de granulação grossa a muito grossa, fortemente unimodal e é classificado como litarenito e subarcósio pela composição modal, que é suportada por estudos geoquímicos. De acordo com petrografia e geoquímica, o arenito Kikhla foi depositado em uma bacia de margem continental passiva, principalmente a partir de fontes graníticas. Com base nas proporções dos principais elementos e na interpretação petrográfica, as rochas-fonte são provavelmente reconhecidas como granitos que foram expostos por meio de rifteamento. Os valores do CIA (Índice Químico de Alteração) (73,28-93,97) indicam um alto grau de intemperismo químico, que pode ser atribuído às condições climáticas áridas na área de origem e controladas principalmente pela proveniência da rocha fonte, seleção hidráulica durante o transporte e deposição, diagênese e ambiente deposicional. De acordo com as investigações químicas, o arenito apresenta concentrações significativas de SiO_2, $Na_2O>K_2O$ e Fe_2O_3, o que é compatível com os dados modais.
Palavras-chave: Margem continental ativa. Formação Kikhla. Arenito quartzítico. Intemperismo químico. Classificação hidráulica. Proveniência da rocha-fonte.

ABSTRACT - This study aims to determine and investigate the provenance of the source rocks and the depositional setting of the Kikhla Formation, Lower Cretaceous, northwestern Libya. It is mainly composed of mature quartzitic sandstone alternating with conglomerate and clay. The study proved that the sandstone is yellow-white in color and commonly carries quartz granular and small fragments of silicified wood. The environmental deposition is under differing fluvial conditions and by a large braided river. Texturally, the Kikhla sandstone is poorly cemented, coarse to very coarse grained and strongly unimodal and is classified as litharenite and subarkose by the modal composition, which is supported by geochemical studies. According to petrography and geochemistry, the Kikhla sandstone was deposited in a passive continental margin basin, mainly from granitic sources. On the basis of major elements ratios, and petrographic interpretation, the source rocks are most likely recognized as granites that were exposed via rifting. The CIA (Chemical Index of Alteration) values (73.28-93.97) indicate a high degree of chemical weathering, which could be attributed to the arid climate conditions in the source area and mainly controlled by the source-rock provenance, hydraulic sorting during transport and deposition, diagenesis and depositional environment. According to chemical investigations, sandstone exhibits significant concentrations of SiO_2, $Na_2O>K_2O$, and Fe_2O_3, which is compatible with the modal data.
Keywords: Active continental margin. Kikhla Formation. Quartzitic sandstone. Chemical weathering. Hydraulic sorting. Source-rock provenance.

INTRODUCTION

The geochemical behavior of clastic sediments is the result of a complex interaction in an open system, it starts with diagenesis and ends with the sedimentation process, passing through chemical weathering and transportation. Their complex chemical process reflects the difference in the variable chemical signatures. Certain factors, such factors as the tectonic settings, climate dependent weathering, hydraulic sorting during transport and deposition, depositional environment and diagenesis and source materials play an important role in the scenario of diagenesis of the Kikhla sandstone.

This study is a unique case study, it is due to the thickness of the formation, where the sediment thickness exceeds (200 m) and the geological time interval of the digenesis a under different tectonic settings and depositional environments. Several studies have made significant contributions to the facies and stratigraphy of the Lower Cretaceous Kikhla Formation in northwest Libya (Assereto and Benelli, 1971; Burollet, 1963; Busson, 1967; Cate and Hammuda, 1969, Hammuda 2000; Christie, 1955; Desio et al, 1960; El Zouki, 1980), but no studies dealt with the major and trace-elements and no detailed studies have been conducted on their geochemistry or tectonic setting. The main purpose of this study is to evaluate the major elements geochemistry of the Lower Cretaceous sandstone of Kikhla Formation from exposed sections in the Zintan city (Figure 1) in Jabal Nafusah, northwestern Libya, in order to deduce their provenance, weathering signatures, and the tectonic setting. The study attempted to answer a set of questions, the most prominent of which, if is there evidence in either the Mesozoic or Paleozoic Nubian type sandstone under developed meandering channel or braider fluvial system? If is the depositional environment created from combinations of specific sedimentary processes such as fluvial, estuarine and shallow marine environments? Was it laid down on continental mass in Early Mesozoic?

GEOLOGICAL SETTING

The Kikhla Formation forms a major geological feature in northwestern Libya, extending for about 200 km from Garyan to the Tunisian border (along the escarpment between latitudes 31°04'29.83''N and longitudes 12°26'48.88''E. The study area is bordered by the Jafarah plain (Figure 1). The plain is mostly covered with Cenozoic to Mesozoic deposits and the exposed sedimentary rocks are of the Lower–Upper Cretaceous age.

The Lower Cretaceous Kikhla Formation consists mainly of fluvial sandstones, deposited by braided rivers in northward-flowing, and is a mixture of siliciclastic and carbonate sediments. It overlies unconformably Upper Cretaceous deposits composed of dolomite of the Sidi As Sid Formation and limestone of the Nalut Formation (Figure 2).

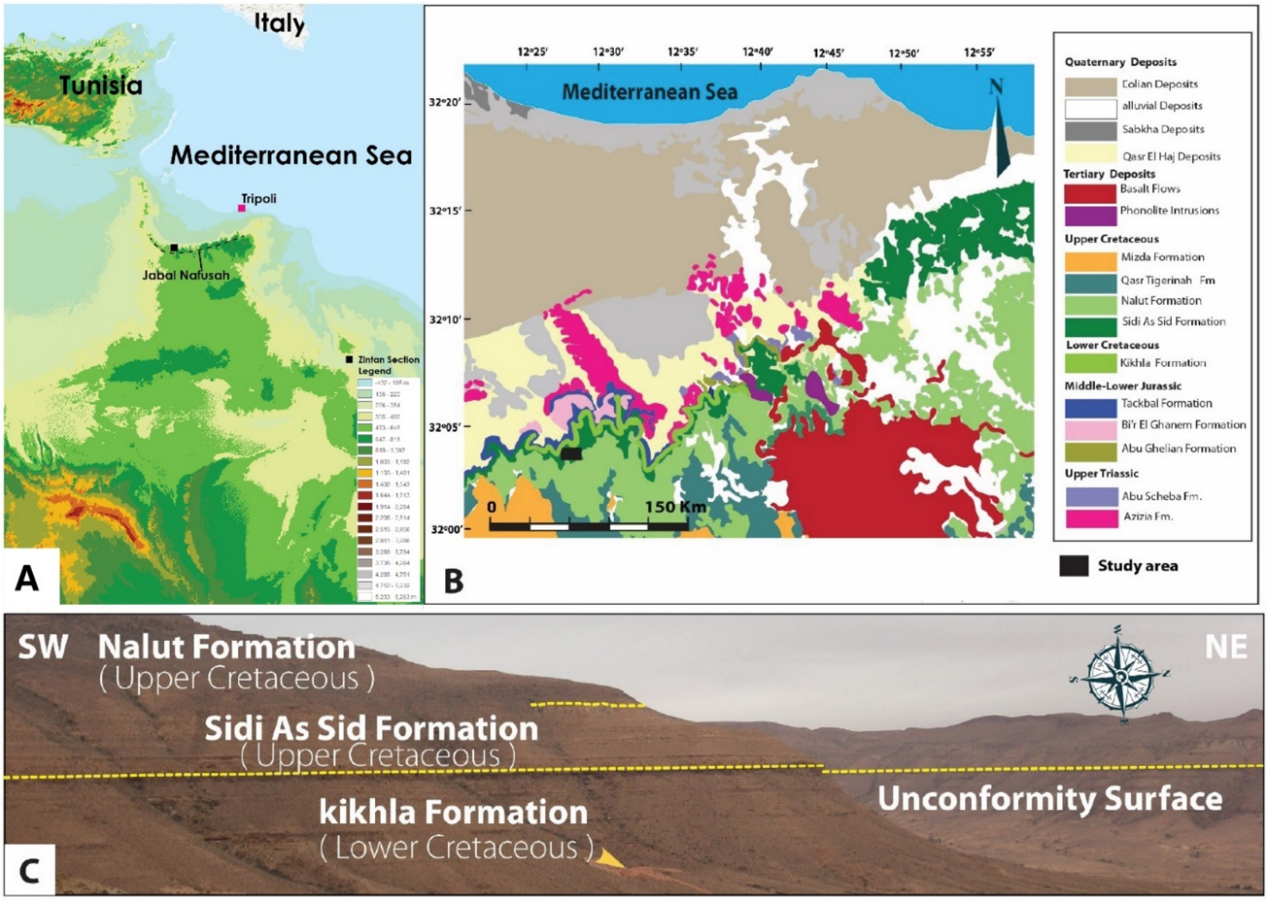

Figure 1 - A). Shows the digital elevation model (DEM) map of the study area (source: databasin.org) and B) the location of the Zintan section c) Shows the study area location and the unconformity surface (Upper Cretaceous) in the Zintan section.

The Kikhla Formation is a major continental clastics and exposed in extensive outcrops, and these continental clastics are considered as a northern extension of the Nubian sandstone, which is widely exposed in southern Libya (El Zouki, 1980; Goudarzi, 1970; Hallett and Clark-Lowes, 2016).

The Lower Cretaceous Kikhla Formation is characterized by gradational contact with yellow-white sandstone beds (Figure 2a). It measures 80-150 m thick at the Zintan-section. It is mostly made up of sandstones, shale and conglomerate (Figure 2b), with cross bedding (Figure 2c). The cross bedding is present, mainly planar with a small to medium scale (5-25 cm). In the Zintan section, the Kikhla Formation sequence averages 80 m in thickness and is dominated by massive, occasionally finely laminated, varicoloured micaceous mudstone and fossiliferous (Figure 2 d & e). At the base of the sequence displays the mudstone interbedded thin sandstone units, while in the upper parts of the section there is an increase of more carbonatic-clastic. Texturally, Kikhla sandstone is unimodal and moderately well sorted. However, the depositional environment is considered as strong evidence of deposition by a braided alluvial system and is dominated by gentle current activity in a relative low energy environment. These characteristics may indicate evidence of sediments reworking.

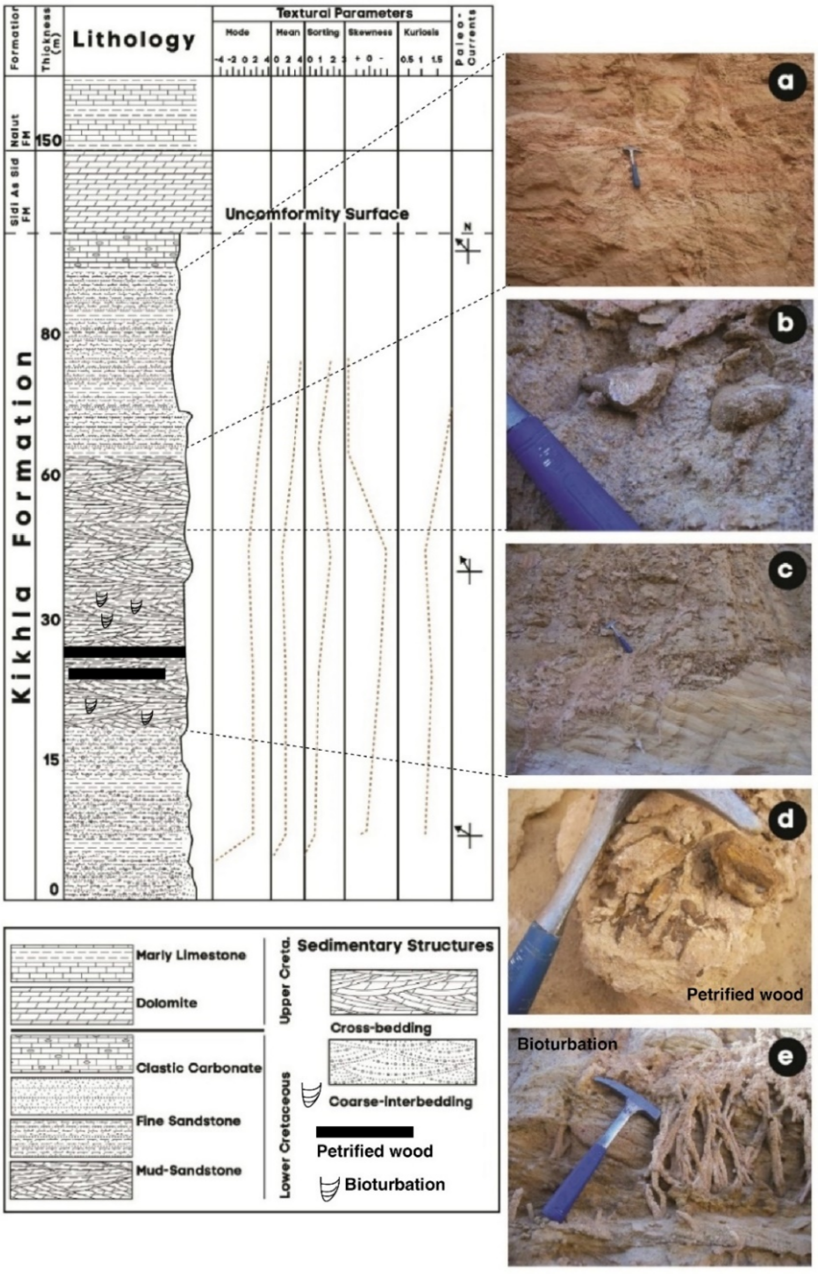

Figure 2 - Chart of the studied section and the lithofacies distribution of the Kikhla Formation: (a). Sandstone is yellow-white in color with cross-bedding (b). Conglomeratic sandstone (c). Gradational contact is characterized by a fine yellow sandstone bed. (d and e) Petrified wood and fossiliferous sandstone (Bioturbation).

MATERIALS AND METHODS

Fresh samples of sandstone were collected from an exposed outcrop in Jabal Nafusah near the Zintan city. Thin sections were chosen for detailed petrographic using optical microscopy. To reduce the dependence of rock composition on grain size, point counts were performed using the Dickinson model (Dickinson, 1970). The major geochemistry of all eight samples was determined on fused beads, the major oxides were determined using an X-ray fluorescence (XRF) spectrometry technique. Mineral compositions were determined by microanalysis of heavy mineral grains using a scanning electron microscope (SEM).

RESULTS

Petrography

The majority of samples of the Kikhla Formation are mainly characterized by medium to coarse grain, rounded to subangular and poorly sorted.

The framework grains of the sandstone consist of monocrystalline quartz, dominated by K-feldspar and rock fragments. The most abundant framework grain in sandstone is quartz, which has a sub-rounded to subangular shape (Figure 3a). The detrital matrix is mainly fine-grained. Multiple deformation fractures can be seen in some of the quartz grains (Figure 3a).

Quartz grains are spherical, devoid of etching and devoid of overgrowth, mostly made up of non-oriented crystallites with straight to undulose extinction (Figure 3b) and inclusions are present. The various surface features observed are broadly differentiated into two types, chemical weathering features and mechanical or abrasive features. Other chemical aspects such as oriented pitted and etched surfaces and meandering to straight grooves were also observed. These diagenetic features are developed by chemical activity either during or after the deposition of sediments. The sandstones contain feldspars, which make up 14.3% of the volume of the rock on average. Photomicrograph (Figure 3c) shows authigenic kaolinite (Kln) with a “worm-like”. The grains are subangular and free of inclusions. The SEM (Scanning Electron Microscope) analysis of sand grains from the Kikhla Formation provides useful criteria which can serve to distinguish between these continental clastic deposits and to recognize depositional environments. The sand grains of the Kikhla Formation are dominated by V-shaped, large and small conchoidal breakage patterns (Figure 3d) impact pitting of various shapes, angular grains, meandering to straight (Figure 3d) oriented pitting and etching with crystal growth, oriented deep surface etching, and chemically indented meandering and curved grooves (Figure 3f).

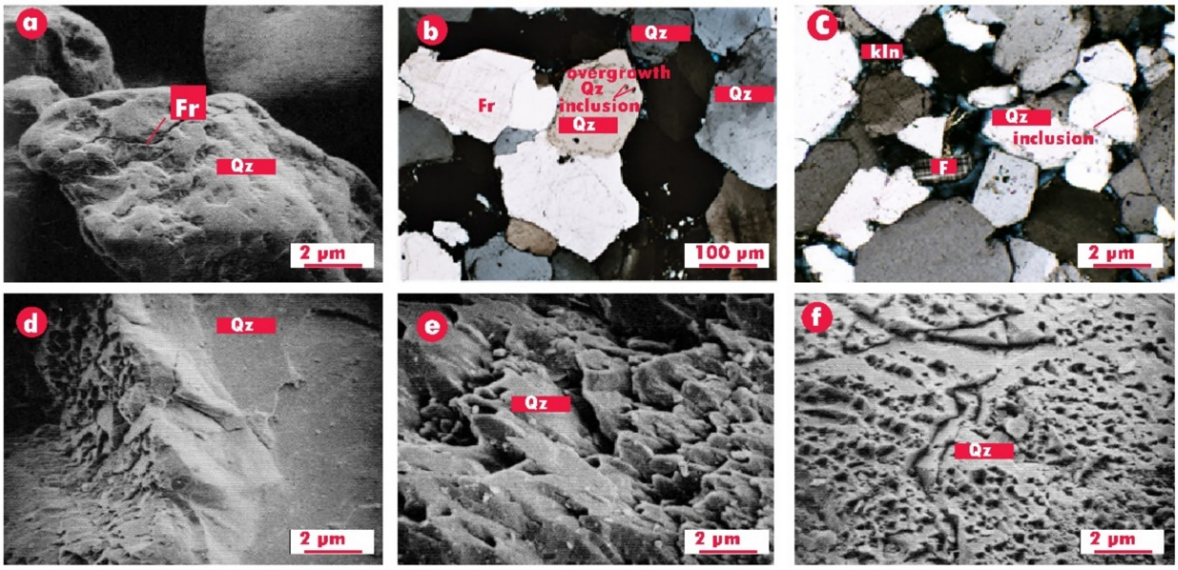

Figure 3 - a) Photomicrograph and SEM of the Kikhla sandstone Formation, quartz (Qz) grain surface shows V-shapes, impact pitting, grooves and conchoidal fractures (Fr). The fractures which resulted from grain collisions during transportation by alluvial currents b) Monocrystalline quartz with overgrowth and inclusions. (c) This sandstone includes clasts of monocrystalline quartz and partially altered feldspar (F) (sodium feldspar) and exhibits parallel twinning that gives it a striped appearance. d) blocky conchoidal breakage patterns in the centre, and oriented V-shapes developed by chemical etching. e) oriented surface etching and chemically indented meandering and curved grooves. f) curved grooves features.

The modal heavy minerals include the ubiquitous, transparent, zircon and rutile (Figure 4 a and b) are mainly hematite as a cement and as an alteration product of ilmenite and less commonly ilmenite and fossilized woods (Figure 4c).

The subarkosic arenites (Figure 4d) indicate strong weathering conditions dominating the source rocks and affecting the sediments during the long fluvial pathway, or the recycling of older sedimentary rocks preferentially from the coarser sand fractions by abrasion strata with high degree of roundness during transport, owing to their mechanical instability (Figure 4e).

In other words, this could be attributed to derivation from the granitoid source rocks, whereas the quartz arenites were derived from the Paleozoic-Mesozoic siliciclastic rocks. Quartz grains are moderately sorted, medium in size and poorly cemented in sublithic arenite and have multiple deformation fractures (Figure 4f, g).

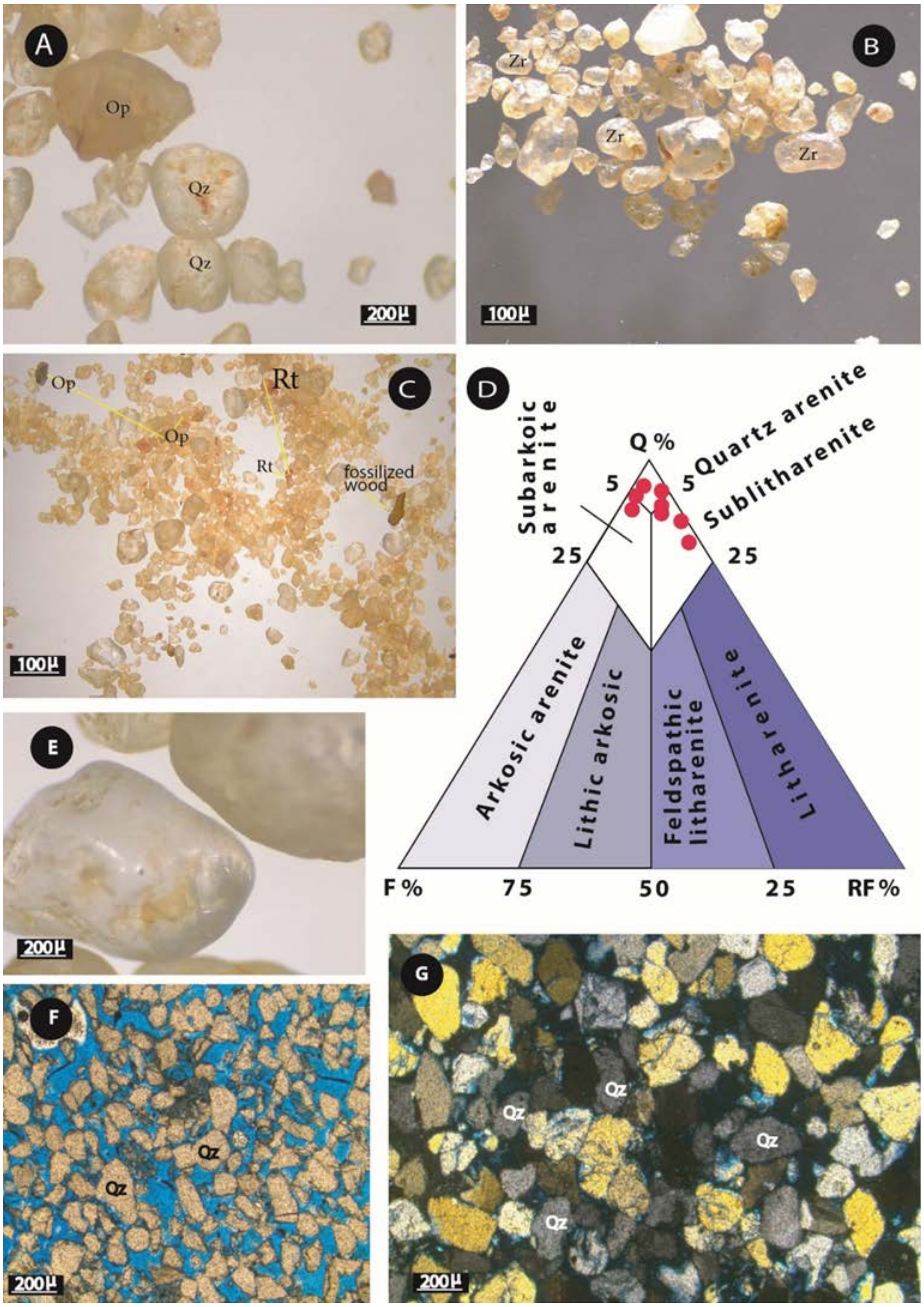

Figure 4 - a) Photomicrograph of moderately sorted and poorly cemented quartz sublithic arenite b, c) showing photomicrograph of detrital (heavy minerals) and optical minerals and petrified woods. d) classification of quartz-feldspar-rock fragments (after Amireh 2018). e) photomicrograph of detrital quartz grains of the sand fraction by abrasion strata with high degree of roundness. f) medium in size quartz grains, moderately sorted and have multiple deformation fractures of Kikhla sandstone. g) quartz grains are heterogeneous mixture of mostly rock fragments and clay.

Major element geochemistry

The major-elements are listed in table 1 and figure 5 illustrates the chemical variability of the major elements in a box-whisker chart. Parallel lines extending from the boxes indicates variability outside the top and bottom quartiles. According to the chemical variability of major elements, SiO_2, Al_2O_3 and CIA (Chemical Index of Alteration) values exhibit significant outliers and chemical variability (Figure 5). In accordance with the geochemical classification diagram of log (SiO_2 /Al_2O_3) -log (Na_2O/K_2O) (after Pettijohn et al., 1972), the Kikhla sandstone is classified as litharenite ,sublitharenite and subarkose (Figure 6a). This classification is supported by petrographic evidences: High enrichment of SiO_2 content in subarkose (Z4, Z5-Z7 samples). Similarly, Al_2O_3 content is high in subarkose. TiO_2 concentrations are generally low, particularly in subarkose. The average Na_2O content for the Kikhla sandstone subarkose; (average of 0.26), litharenite and sublitharenite; (average of 1.03) is more than 1%. Also, the depletion of Na_2O (>1.0%) in studied sandstone, attributed to a relatively higher amount of sodium oxide. Alkali contents (average ;1.23) dominates K-feldspar over plagioclase.

On the other hand, the Al_2O_3/TiO_2 vs. SiO_2 plot shows that samples of the Kikhla Formation are felsic (Figure 6b) except for one sample that falls into mafic composition. The data point to a major, felsic provenance that must have consisted of granitoids, mainly granite, and less commonly granodiorites, gneisses or schists. On the other hand, the minor degree of recycled, siliciclastic provenance was due to the contributions from the Lower Palaeozoic strata that supplied detritus to the middle and Upper Paleozoic deposits.

Table 1 - Major elements (wt%) from the Kikhla Formation, NW Libya.

Sample	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8
SiO_2	66.7	66.7	70.3	95.4	95.8	86.8	93.4	45.2
TiO_2	0.6	0.5	0.2	0.2	0.2	0.3	0.1	0.7
Al_2O_3	3.5	2.6	6.5	5.2	7.8	6.7	3.26	4.5
Fe_2O_3	1.6	1	5	1.7	1.7	1.2	2.1	4.3
FeO	3.5	0.2	2	0.1	0.1	0.2	0.1	1.2
MnO	0.1	0.1	0.2	0.02	0.02	0.05	0.05	0.04
CaO	0.02	0.09	0.03	0.02	0.05	0.01	0.01	0.01
MgO	2.1	0.2	5.3	0.12	0.1	0.1	0.04	1.8
Na_2O	2.9	0.1	0.3	0.2	0.3	0.3	0.3	1.55
K_2O	2	0.05	0.05	0.14	0.15	0.2	0.1	1.25
P_2O_3	0.2	0.05	0.05	0.04	0.03	0.05	0.05	0.01
H_2O	3	0.2	0.1	0.1	0.1	2.4	1	0.2
Fe_2O_3+MgO	3.7	1.2	10.3	1.82	1.8	1.3	2.14	6.1
K_2O/Na_2O	0.69	0.5	0.17	0.7	0.5	0.67	0.33	0.81
CIA	41.57	91.55	94.48	93.53	93.98	92.93	88.83	61.56
Al_2O_3/TiO_2	5.83	5.2	32.5	26	39	22.33	32.6	6.43
SiO_2/Al_2O_3	19.06	25.65	10.82	18.35	12.29	12.95	28.66	10.03

DISCUSSION

Provenance and source area

Trace elements have an increasingly important role in understanding the source and provenance of sandstones. According to the petrographic analysis, the sandstone has a granitic source based on the average composition of various quartz grains. Verma (2001a, 2001b) indicates the probable bivariate plot of source rock K_2O/Na_2O–SiO_2/Al_2O_3 shows that the Kikhla sandstone are granitic sources (Figure 7a). These have been supported by a general change in the relative abundance of various quartz grains, including both monocrystalline (undulatory and non-undulatory) and polycrystalline grains.

The lower abundance of plagioclase than of alkali feldspar provides more evidence for the granitic source and felsic provenance (Figure 7b). Petrographically, K-feldspar predominates over plagioclase, which could be due to intense weathering in the source area or diagenetic change (Figure 8).

The presence of abundant carbonate cement, which formed most likely during diagenesis, rules out the latter Armstrong-Altrin et al., (2004).

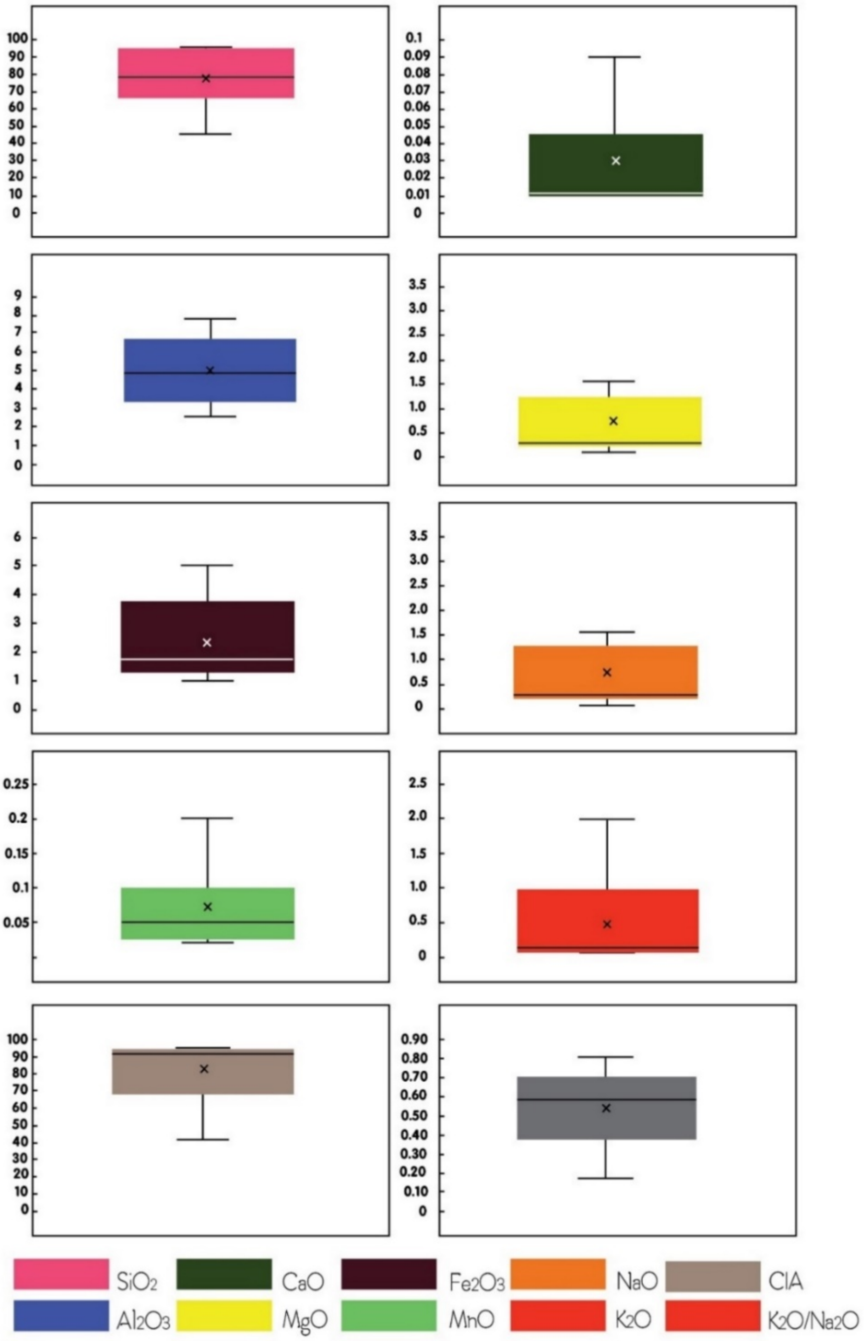

Figure 5 - Box-whisker diagram (%) for the major elements and CIA* of Kikhla Formation. The lines extending parallel to the boxes represent variability outside the upper and lower quartiles (Q3 and Q1). The x inside the box represents the median and the line represents the mean.

From another point of view, during the chemical weathering of granite, the alteration of feldspars is the dominant process. On the other hand, other elements such as Ca^{2+}, Na^{+}, and K^{+} are mobile in the water-rock system during the weathering and transportation, and are largely removed from feldspars (Nesbitt et al., 1980, 1997).

Moreover, minerals such as rutile and zircon accumulate in the weathering residue and are transported with little chemical alteration. The Chemical Index of Alteration - CIA (Nesbitt and Young, 1982); McLennan et al., 1993). is widely used to determine the chemical weathering in a source area. The CIA values of the Kikhla sandstone indicate a moderate to strong degree of chemical weathering, which may reflect hot and/or humid climate conditions in the study area. In sedimentary rocks, particularly sandstones, maturity describes grain composition and texture. The Al_2O_3-CaO + Na_2O-K_2O (A-CN-K) ternary diagram (Nesbitt and Young 1982,1984) can also be used to identify paleoweathering conditions (Figure8).

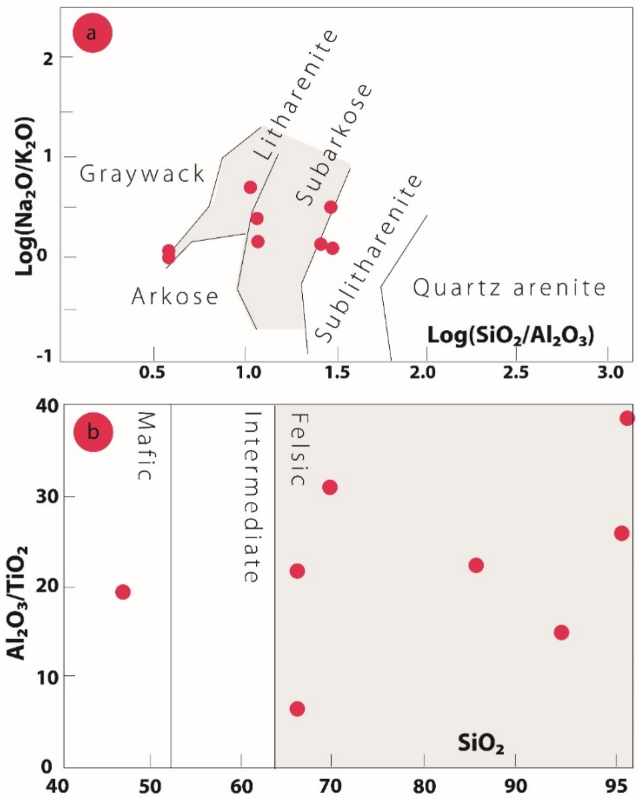

Figure 6 - a). Geochemical classification of Kikhla sandstone using log (SiO2/Al2O3)-log(Na2O/K2O) diagram (after Pettijohn et al., 1972) .b) SiO2 vs. Al2O3/TiO2 diagram (after Le Bas et al., 1986).

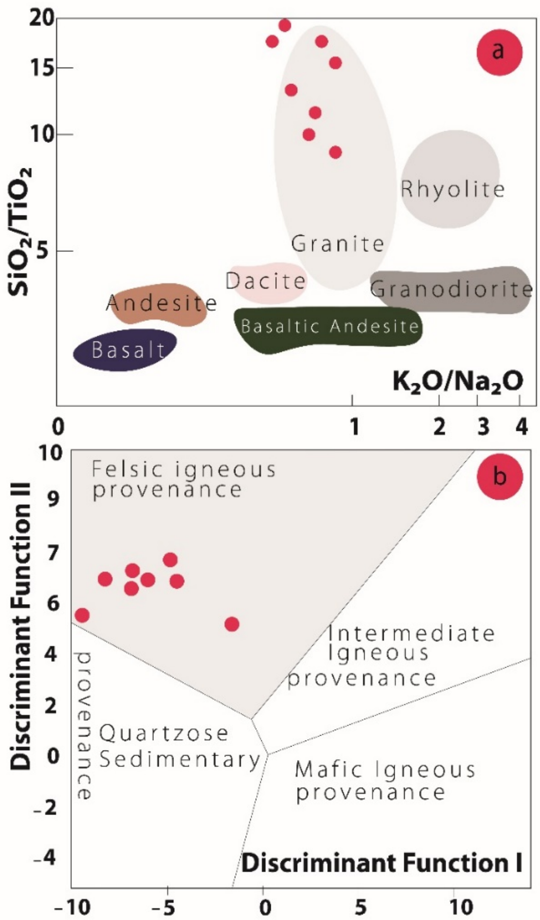

Figure 7 - (a) Al_2O_3/TiO_2 vs. (SiO_2) relationship for the Kikhla Formation (Le Bas et al., 1986). (b) Discriminant function diagram for the Kikhla sandstone (Verma 2001a, 2001b) Discriminant Function I = (-1.773 TiO_2) + (0.607 Al_2O_3) + (0.760 Fe_2O_3) + (-1.500 MgO) + (0.616 CaO) + (0.509 Na_2O) + (-1.224 K_2O) +(-9.090). Discriminant Function II = (0.445 TiO_2) + (0.070 Al_2O_3) + (-0.250 Fe_2O_3) + (-1.142 MgO) + (0.438 CaO) + (1.475 Na_2O) + (-1.426 K_2O) + (6.861).

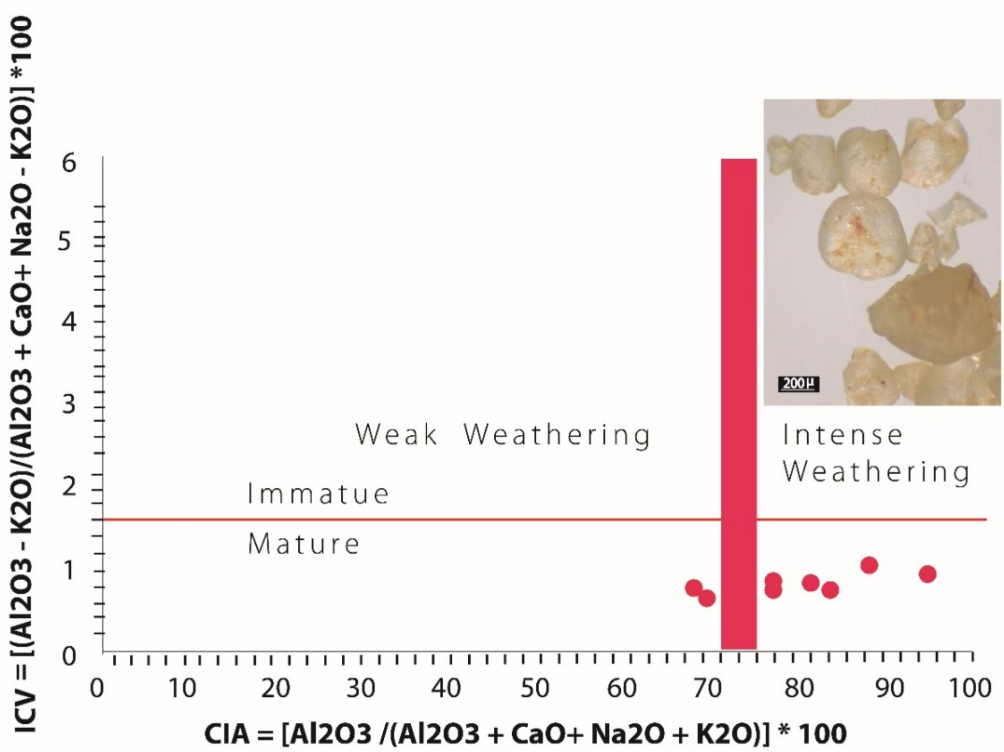

Figure 8 - Binary plot of CIA against ICV (Index of Compositional Variability) for the Kikhla Formation samples. Piper et al. (2008).

The Kikhla sandstone plots near the granite line (Figure 9a), and this scatter reveals steady state weathering conditions that exist where tectonic activity and climate are highly variable. These conditions change the rates of erosion and chemical weathering, which leads to the production of sediments with a variety of chemical compositions (Nesbitt et al., 1997). The presence of clay minerals, which are thought to have inherited kaolinite from weathering layers and soils formed on silicic (granitic) rocks, further supports this (Figure 9a).

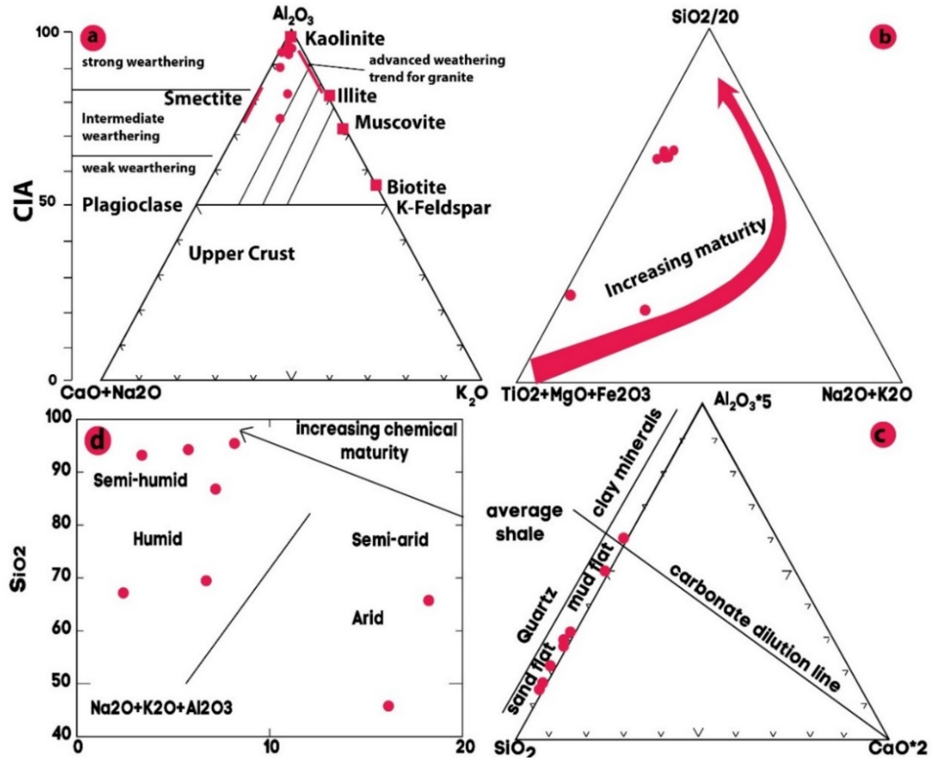

Figure 9 - a). Al_2O_3 – ($CaO + Na_2O$) – K_2O ternary diagram for the Kikhla sandstone after Nesbitt and Young (1984). b) sandstone maturity as a function of wt.% $SiO_2/20$, $K_2O + Na_2O$, and $TiO_2 + MgO + Fe_2O_3$ (after Kroonenberg, 1990). c). Ternary plot $Al_2O_3{\times}5$–SiO_2–$CaO{\times}2$ (Brumsack, 1989). d) Plot of SiO_2 (reflective of quartz content) versus K_2O+Na_2O+Al_2O_3 (reflective of feldspar content).

Sandstone geochemistry can be used to distinguish between mature and immature varieties using the relative abundances of quartz, feldspar + clay, and ferromagnesian minerals. Prolonged weathering breaks down ferromagnesian minerals and so depletes the sediment in Ti^{2+}, Mg^{2+}, Fe^{3+}. In a similar way, through the breakdown of feldspars and micas, the sediment is depleted of K + Na. This gives rise to an increase in residual quartz (SiO_2) and a high level of compositional maturity as illustrated in Figure9b. The major element compositions of the investigated Kikhla sand are shown in the ternary plot Al_2O_3×5-SiO_2-CaO×2 (Figure 9c). Apparently, the investigated sandstone presents minor amounts of carbonate, the bivariate plot of SiO_2 (reflective of quartz content), against K_2O+ Na_2O+Al_2O_3 (reflective of feldspar content) represents the chemical maturity, trend as a function of climate (Dickinson and Suczek, 1979); Suttner and Dutta, 1986). The K_2O/Na_2O ratio values indicate derivation from granite rather than basic rocks and can be used as provenance indicator. The plotted samples revealed semi-humid to humid climatic conditions in the area, which tend to increase chemical maturity. Overall, the sand plotted in the semi-humid region may has experienced more chemical weathering and is mature (Figure 9d). The rift basins are characterized by mature minerals sandstone and the presence of lithare-nite and subarkose, due to the possibility that the sediment originated in uplifted horsts along the rift, where erosion of the exposed crystalline basement beneath the sedimentary cover, this scenario is similar to the Kikhla sandstone.

Tectonic setting

Basin instability quickly buried sediments in the source area and most of them retained their original composition. However, there are lithic fragments and feldspars that have changed because of chemical weathering, which can change sandstone make-up more than anything else (Suttner and Dutta, 1986). The observations show that the Kikhla Formation's sandstone may have come from granitic source rocks (felsic provenance). This idea is also supported by the fact that alkali feldspars are present, which shows that they came from plutonic rocks (Trevena and Nash, 1981). There is an important role for discriminate function diagrams (Roser and Korsch, 1986) in determining the tectonic position of the source rock.

The discriminate function diagram (Roser and Korsch, 1986) shows that the source material was put down in a passive continental margin setting (Figure10a). Verma and Armstrong-Altrin's (2013) proposed a tectonic discriminant-function diagram suggests a rift and collision settings for the Kikhla sandstone (Figure10b).

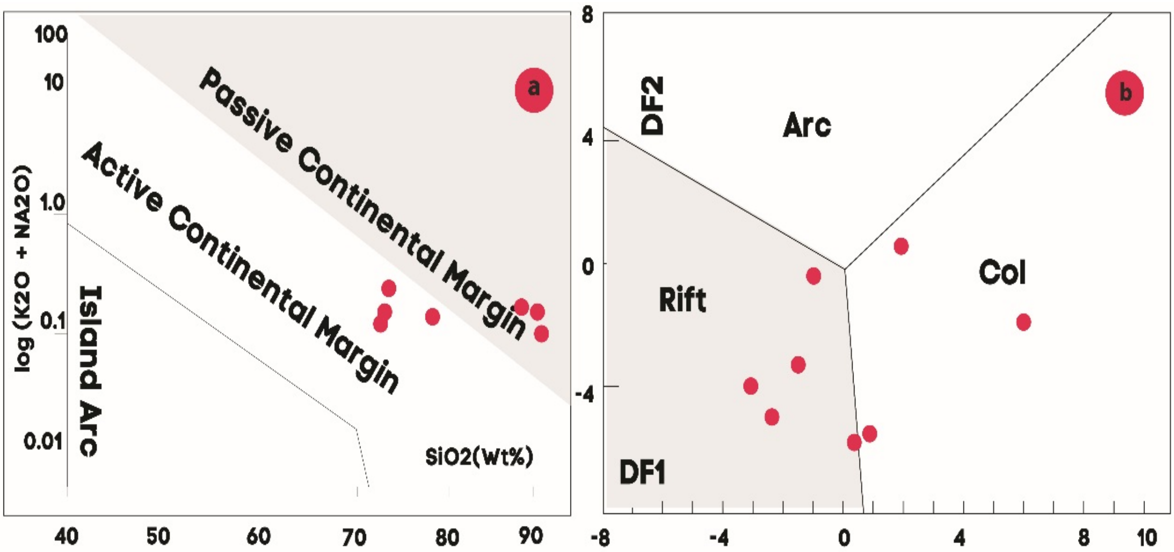

Figure10 - a). The bivariate plot of SiO_2 versus K_2O/Na_2O for the studied samples shows tectonic setting after Roser and Korsch, R.J. (1986) b). discriminant-function diagram Verma and Armstrong-Altrin (2013) for high-silica clastic sediments. In DF1 and DF2, represent the high-silica diagram based on log e-ratios of major-elements. The discriminant function equations are as follows: **DF1(Arc-Rift-Col)**= (-0.263 In(TiO_2/SiO_2) adj) + (0.604 - In(Al_2O_3/SiO_2)adj) + (-1.725 - In(Fe_2O_3t/SiO_2)adj) + (0.660 - In(MnO/SiO_2)adj) + (2.191 - In(MgO/SiO_2)adj) + (0.144 - In(CaO/SiO_2)adj) + (-1.304 - In(Na_2O/SiO_2)adj) + (0.054 - In(K_2O/SiO_2)adj) + (-0.330 In(P_2O_5/SiO_2)adj) + 1.588. **DF2(Arc-Rift-Col)**= (-1.196 - In(TiO_2/SiO_2) adj) + (1.604 - In (Al_2O_3/SiO_2)adj) + (0.303 - In(Fe_2O_3t/SiO_2)adj) + (0.436 - In(MnO/SiO_2)adj) + (0.838 - In(MgO/SiO_2)adj) + (-0.407-In(CaO/ SiO_2)adj) + (1.021 - In(Na_2O/SiO_2)adj) + (-1.706 - In(K_2O/SiO_2)adj) + (-0.126 – In (P_2O_5/SiO_2)adj) - 1.068.

The tectonic setting of the studied area can also be briefly summarized. The study area was a part of the Jifarah basin in northwest Libya, which slopes towards the Mediterranean and extends westward into Tunisia. An east-trending pre-Miocene fault forms the southern boundary. The Jifarah basin was part of the marginal trough probably through most of the Palaeozoic and early Mesozoic Eras, but in Late Cretaceous time it was a stable platform, and little sediment accumulated from this time on into the Miocene. The Caledonian, Hercynian, Cretaceous, middle Tertiary (Oligocene to Miocene), and Holocene events brought on uplifts, subsidence, tilting, and faulting and intrusions. Finally, the Proterozoic granite could have been the source rock for the Kikhla sandstone, which has been uplifted and exposed by the Rifting Orogeny (Hammuda 2000).

The main tectonic elements of the study area and the schematic cross-section are summarized in Figure 11. They include the older Caledonian orogenic elements, manifest in the Nafusah uplift, the Gargaf uplift. The northern part of the study area was uplifted during the Hercynian folding (Burollet, 1978) but subsided again during the early Mesozoic. It was uplifted again near the end of Cretaceous time, the uplift being accompanied by northwest trending faults, while the old highs, displaced the Jifarah basin to the north and Al Qarqaf (Figure 11c) to the south, were reactivated in Late Cretaceous or Early Paleocene time (Jordi and Lonfat, 1963). Precambrian rocks form an extension of the Tibisti Uplift under the Nafusah Arch, extending to over 5000 meters offshore (Hammuda, 2000).

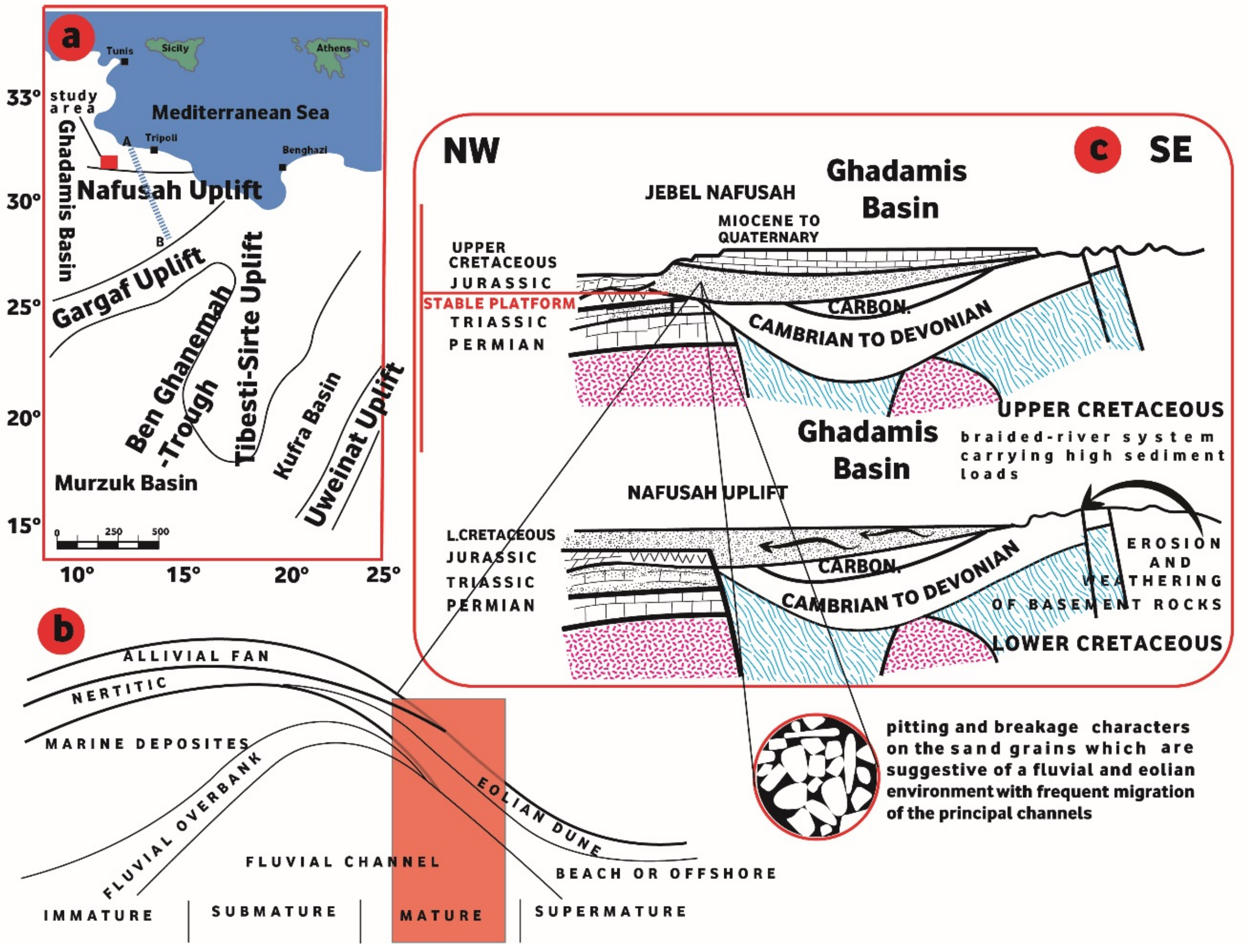

Figure11 - a). major structural elements in NW Libya. (modified from Klitzsch, 1971). b) textural maturity of Khikhla sandstone (after Folk, 1951). c) schematic cross-section along NW-SE showing the structural development of Libya (modified Klitzsch, 1971).

During the Late Cretaceous period, rocks of the Upper Cretaceous period formed the cap on the escarpment of the Nafusah Jabal and the center of the escarpment. During Pliocene and Pleistocene time, continental deposits have been accumulated over eroded Mesozoic and continued to the present. According to Folk (1951), Khikla sandstone is mature sandstone, parti-cularly, characteristic of fluvial channels, and eolian dunes (Figure 11b) because of the high energies and abrasive potential of these environments. Most of the sand-sized and finer particles are carried along in a traction carpet moving just above the surface, and the individual grains move by saltation and intergranular collision. As a result, eolian sands tend to be very well sorted and well rounded (Figure 11c), with pitting and frosting Folk (1951). The Kikhla sandstone is texturally mature and derived from a relatively low-lying granite source, supplemented by recycled sands from the passive margin basin (Figure 11c). The significant proportion of unstable grains (feldspar and other rock fragments) shows that these sandstones were transported across great distances and were quickly buried. This indicates that the sandstones of the Kikhla Formation are typical rift sandstones, and that their deposition constrained the beginning of uplift in the study area.

CONCLUSIONS

The Khikla Formation, which consists of sandstone and shale layers, relates to shallow warm agitated environments and was deposited in a fluvial environment by braided and high-gradient streams with local modifications. The Kikhla sandstone is yellowish white in color, calcareous and fossiliferous, classifying them as litharenite, sublitharenite and subarkose with subordinate, which is also supported by geochemical study. Chemical analysis showed that sandstone has high SiO_2, K_2O>Na_2O low MnO, Fe_2O_3, and MgO values. The Khikla sandstone is texturally mature and derived from a relatively granite source.

The high percentage of unstable grains (feldspar and other rock fragments) >15%, indicates that the sandstone has a long transport distance.

The CIA value may be due to direct input of immature continental detrital minerals into the depositional system. The source of the sediments of the Khikla sandstone was felsic igneous rocks with mature polycyclic continental sedimentary rocks (Roser and Korsch, 1986)

ACKNOWLEDGMENT

The author is grateful for the very constructive comments and editorial comments made by the journal reviewers and editors that improved the manuscript.

REFERENCES

AMIREH, B.S. Petrogenesis of the NE Gondwanan uppermost Ediacaran-Lower Cretaceous siliciclastic sequence of Jordan: Provenance, tectonic, and climatic implications. **Journal of Asian Earth sciences**, v. 154, p. 316-341, 2018. https://doi.org/10.1016/j.jseaes.2017.12.037

ARMSTRONG-ALTRIN, J.S.; LEE, Y.I.; VERMA, S.P.; RAMASAMY, S. Geochemistry of sandstones from the Upper Miocene Kudankulam Formation, southern India: implications for provenance, weathering, and tectonic setting. **Journal of Sedimentary Research**, v. 74, p. 285–297, 2004. https://doi.org/10.1306/082803740285

ASSERETO, R. & BENELLI, F. **Sedimentology of the pre-Cenomanian Formations of the Jebel Gharian, Libya.** In: SYMPOSIUM ON THE GEOLOGY OF LIBYA (ed. C. Gray), Tripoli, Faculty of Science, University of Libya, Tripoli, p. 37-85, 1971.

BRUMSACK, H.-J. Geochemistry of recent TOC-rich sediments from the Gulf of California and the Black Sea.20 **Geologische Rundschau**, v. 78, n. 3, p. 851-882,1989.

BUROLLET, P.F. **Field Trip Guidebook of the Excursion to Jebel Nefusa Petroleum Exploration Society of Libya**. In: SAHARAN SYMPOSIUM, 1, Tripoli, 19, 1963.

BUROLLET, P.F.; MUGNIOT, J.M.; SWHIEENIY, P. The Geology of the Pelagian Block; the margins and basins off southern Tunisia and Tripolitania. In: **The Ocean Basins and Margins** (eds A.E.M. Nairn, W.H. Kanes and F.G. Stehl). Plenum Press, New York, 331-359, 1978.

BUSSON, G. Mesozoic of southern Tunisia. In: Guidebook to the Geology and History of Tunisia (ed. L. Martin) Petroleum Exploration Society of Libya, 9th **Annual Field Conference**, 131-151, 1967.

CATE, A. & HAMMUDA, O.S. **Road Log and Map for Jebel Nefusa**. Field Trip Geology of Libya Symposium. Department of Geology, University of Libya. p. 15, 1969.

CHRISTIE, A.M. **Geology of the Garian area, Tripolitania, Libya**. U.N. Technical Assistance Program, Report. TAA/Lib/2, p. 60, 1955.

DESIO, A.; RONCHETTI, R.C.; AND INVERNIZZI, G. Il Giurassico dei dintorni di Jefren in Tripolitania. Riv. **Ital Paleontol. Stratigr**. v. 66, p. 65-118, 1960.

DICKINSON, W.R. & SUCZEK, C.A. Plate tectonics and sandstone compositions. **American Association of Petroleum Geologist Bulletin,** v. 63, n. 12, p. 2164–2182, 1979. https://doi.org/10.1306/2F9188FB-16CE-11D7-8645000102 C1865D

DICKINSON, W.R. Interpreting detrital modes of greywacke and arkose. **Journal of Sedimentary Research**, v. 40, p. 695–707, 1970. https://doi.org/10.1306/74D72018-2B21-11D7-8648000 102C1865D

EL-ZOUKI A**. Stratigraphy and Lithofacies of the Continental Clastics (Upper Jurassic and Lower Cretaceous) of Jabal Nafusah, NW Libya**. In: SYMPOSIUM ON THE GEOLOGY OF LIBYA, v. 2, p. 393-418, 1980.

FOLK, R.L. Stages of textural maturity in sedimentary rocks. **Journal of Sedimentary Petrology,** v. 21, p. 127–130, 1951.

GOUDARZI, G.H. Geology and mineral resources of Libya A reconnaissance U.S. **Geological survey professional Pape**r, v. 660, p. 104, 1970.

HALLETT, D. & CLARK-LOWES, D. **Petroleum Geology of Libya**. 2nd Edition. Elsevier Inc. 392 p., 2016.

HAMMUDA O.SMesozoic and Cenozoic History of the Jifarah Arch, NW Libya and SE Tunisia. **Geology of northwest Libya**. v. 1, p. 39-47, 2000.

JORDI, H.A. & LONPAF, F. Stratigraphic subdivision and problems in upper Cretaceous-lower Tertiary deposits in north-western Libya. **Rev. Inst. Fr. Parole**., v. 18**, p.** 1428 -1436, 1963.

KLITZSCH, E. **The Structural Development of Parts of North Africa since Cambrian Times**. In: Gray, C., Ed., In: FIRST SYMPOSIUM ON THE GEOLOGY OF LIBYA, 1, 1971. Tripoli. Faculty of Science, University of Libya, p. 253-262, 1971.

KROONENBERG, S.B. Geochemistry of quaternary fluvial sands from different tectonic regimes, **Chemical Geology**, v. 84, p. 88-91, 1990. https://doi.org/10.1016/0009-2541(90) 90172-4

LE BAS, M.J.; LE MAITRE, R.W.; STRECKEISEN, A.; ZANETTIN, B., A Chemical Classification of Volcanic Rocks Based on the Total Alkali-Silica Diagram. **Journal of Petrology,** v. 27, p. 745-750, 1986. https://doi.org/10.1093/petrology/27.3.745

MCLENNAN, S.M.; HEMMING, S.; MCDANIEL, D.K.; HANSON, G.N. Geochemical Approaches to Sedimentation, Provenance and Tectonics. In: Johnsson, M.J. and Basu, A., Eds., Processes Controlling the Composition of Clastic Sediments. **Geological Society of America, Special Papers,** v. 285, p. 21-40, 1993. http://dx.doi.org/10.1130/SPE284-p21

NESBITT, H.W. & AND YOUNG, G.M. Prediction of Some Weathering Trends of Plutonic and Volcanic Rocks Based on Thermodynamic and Kinetic Considerations. **Geochimica et Cosmochimica Acta,** v. 48, p. 1523-1534, 1984. http://dx.doi.org/10.1016/0016-7037(84)90408-3

NESBITT, H.W.& YOUNG, G.M. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. **Nature**, v. 299, p. 715–717. 1982. http://dx.doi.org/ 10.1038/299715a0

NESBITT, H.W.; FEDO, C.M.; YOUNG, G.M. Quartz and Feldspar Stability, Steady and Non-Steady State Weathering and Petrogenesis of Siliciclastic Sands and Muds. **Journal of Geology**, v. 105, p. 173-191, 1997. https://doi.org/ 10.1086/515908

NESBITT, H.W.; MARKOVICS, G.; PRICE, R.C. Chemical processes affecting alkalies and alkaline earths during continental weathering. **Geochim. Cosmochim. Act**., v. 44, p. 1659–1666, 1980.

PETTIJOHN, F.J.; POTTER, P.E.; SIEVER, R. **Sand and Sandstones**. Springer Verlag, New York. 618 p., 1972. http://dx.doi.org/10.1007/978-1-4615-9974-6

PIPER, D.J.W.; PE-PIPER, G.; LEDGER-PIERCEY, S. Geochemistry of the Lower Cretaceous Chaswood Formation, Nova Scotia, Canada:Provenance and diagenesis. **Canadian Journal of Earth Sciences**, v. 45, p. 1083–1094, 2008. https://doi.org/10.1139/E08-055

ROSSER, B.P. & KORSCH, R.J. Determination of tectonic setting of sandstone– mudstone suites using SiO2 content and K_2O/Na_2O ratio. **Journal of Geology**, v. 94, p. 635–650, 1986. https://doi.org/10.1086/629071

SUTTNER, L.J. & DUTTA, P.K. Alluvial Sandstone Composition and Palaeoclimate Framework Mineralogy. **Journal of Sedimentary Petrology**, v. 56, p. 329-345, 1986.

TREVENA, A.S. & NASH, W.P. An electron microprobe study of detrital feldspar. **Journal of Sedimentary Petrology**, v. 51, p. 137–150, 1981.

VERMA, S.P. & ARMSTRONG-ALTRIN, J.S. New Multi-Dimensional Diagrams for Tectonic Discrimination of Siliciclastic Sediments and Their Application to Precambrian Basins. **Chemical Geology**, v. 355, p. 117-133, 2013. https://doi.org/10.1016/j.chemgeo.2013.07.014

VERMA, S.P. Geochemical evidence for a Lithospheric source for magmas from Acoculco caldera, eastern mexican volcanic bel**t. International Geology Review**, v. 43, p. 31–51, 2001b.

VERMA, S.P. Geochemical evidence for a rift-related origin of bimodal volcanism at Meseta Rio San Juan, north-central Mexican volcanic belt**. International Geology Review**, v. 43, n. 6, p. 475-493, 2001a.

Submetido em 3 de maio de 2023
Aceito para publicação em 14 de julho de 2023