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Diagenetic Aspects of the Nubian Sandstones, in the Central Eastern Desert, Egypt

Samir M. Zaid, Oussama A. El-Badry and Zein A. Abdelaziz

Geology Department, Faculty of Sciences, Zagazig University, 44511 Zagazig, Egypt

Abstract: In the central Eastern Desert four exposed stratigraphic sections along the Qena - Safaga and Qena - Quseir roads were sampled, described and measured in order to determine the detrital, the authigenic composition and the diagenetic history of the Upper Cretaceous Nubian sandstones. The studied sandstones are composed of quartz and much lesser proportions of feldspars and lithic fragments. Based on their average modal composition, they are classify them as quartz arenites with subordinate quartz wackes. Several diagenetic processes modified the original textural composition of characteristics of the Nubian sandstones. These include (i) compaction, (ii) mechanical infiltration of clays, (iii) cementation, (iv) replacement, (v) alteration and (vi) dissolution oxidation of iron oxides. The diagenetic history of these sandstones includes eodiagenesis, immature and mature mesodiagenesis and telodiagenesis. Dissolution of the unstable components during the mature mesodiagenetic stage, increase the primary porosity of the rocks and greatly enhanced their petrophysical properties as oil reservoirs.

Key wards: Diagenesis • Nubian sandstones • Central Eastern Desert

INTRODUCTION

Exposures of The Nubian sandstones cover a large area of Egypt between Lats. $22^{\circ} - 26^{\circ}$ N and occur as interrupted exposures to Lat. 30° 40'N (Fig. 1) [1]. The term "Nubia", was introduced by Russegar [2] for the thick massive sandstone succession that unconformably covers Precambrian Basement Complex in Nuba (south of Aswan). The term "Nubian Sandstone" has since been applied to numerous sandstone units of similar stratigraphic position throughout North Africa and the Middle East and range in age from the Cambrian to the Late Cretaceous [3 - 6]. The absence or rarely macrofossils and microfossils made it difficult to assign most the Nubian sandstones to definite ages. Their strata are exist in the Carboniferous or older, Permian, Triassic, Jurassic and Cretaceous systems and are separated by well defined marine limestones, dolostones, marls, phosphates, etc. However, it is now believed that the typical Nubian sandstones are

of late Cretaceous age [4]. The thickness of formation in the Eastern Desert is highly variable, depending on the topography of the underlying Precambrian Basement Complex. In the study area it ranges from 120 m to 180 m.

The Nubia Sandstone is considered to be one of the most prolific oil reservoirs in the Gulf of Suez region. According to Alsharhan [7], it represents about 17% of the production potential in the Gulf of Suez.

Although the general characteristics of the Nubia Formation have been studied by many workers, however, a few detailed works have dealt with, petrology, sedimentology and mineralogy [3 - 5, 8, 9]. Also there have been no detailed studies of the diagenetic history of these sandstones. This study three- fold: (i) to determine their detrital and authigenic composition of these sandstones in the central Eastern Desert; (ii) to define their controls on the rock porosity; and (iii) to elucidate the diagenetic history of these sandstone.

Corresponding Author: Samir M. Zaid, Geology Department, Faculty of Sciences, Zagazig University, 44511 Zagazig, Egypt. Tel: +201270456772, E-mail: samir_zaid75@yahoo.com.



World Appl. Sci. J., 36 (6): 789-798, 2018

Fig. 1: Geologic map of the study area showing the locations of the measured stratigraphic sections (modified after the Egyptian Geological Survey and Mining Authority [1]

MATERIALS AND METHODS

In this study, four exposed stratigraphic sections representing the Nubia Formation in the central Eastern Desert were measured, described and sampled (Fig. 2), these sections are located along the Qena - Safaga and Qena - Qusseir roads. Thin sections prepared from fifty blue epoxy- impregnated samples were examined using the binocular microscope. The framework mineral components were counted (400 grains) following Gazzi–Dickins method adopted by Gazzi, [10] and Dickinson [11] and described by Ingersoll *et al.* [12]. Grain sorting was determined applying the standard charts of Beard and Weyl [13]. Identification of the carbonate cements was achieved by staining with an acidic solution of alizarin red and potassium ferrocyanide [14]. The scanning electronic microscope (SEM) equipped with energy-dispersive spectrometer (EDAX) was used to identify the detailed compositional and textural characteristics of the rocks especially those related to their diagenetic aspects. Clay mineral species in the $<2\mu$ m fraction were identified using X-ray diffraction analysis. World Appl. Sci. J., 36 (6): 789-798, 2018



Fig. 2: Lithostratigraphic columns and correlation of the studied sections.

Geological Setting: The study area includes three main lithologic groups: (i) the late Precambrian Basement Complex consisting of highly deformed volcanics and volcanogenic sediments metamorphosed to lower green schist facies; (ii) the Cretaceous to lower Eocene platform sediment any succession up to 600 m thick consisting of of well-bedded sandstones, shales and limestones; and (iii) the Miocene to Recent plain sediments along the Red Sea coastal consisting of conglomerates, marls, evaporites and calcareous reef deposits.

The Nubia Formation lies unconformably on the Precambrian Basement Complex and forms the basal unit of the platform sediment any succession (Fig. 2). The formation can be divided into three lithologically distinct members a lower trough cross-bedded member, a middle tabular cross-bedded member and an upper fine sand and silt member [4, 3, 5]. The basal member typically consists of light yellow to reddish brown, well- sorted, medium- to coarse-grained, clean quartz sandstone and quartz pebble conglomerate. Trough cross-bedding is present, locally,

as white, lavender and yellow stained kaolinitic horizons. The thickness of this member is variable being controlled, at least partly by the relief of the underlying Precambrian depositional surface. It ranges between 12 m and 16 m in sections along the Qena - Safaga road and 8 m and 30 m in those along the Qena - Quseir road. The middle member of the Nubia Formation is made up of brown, fine- to medium-grained quartz sandstone with prominent tabular cross-bedding the sets of which average less than 0.5 m in thickness. This member is fairly resistant to weathering and thus is the most conspicuous outcropping unit, commonly forming prominent cliffs. Its thickness ranges from 12 m to 15 m in sections along the Qena - Safaga road and from 10 m to 32 m in those along the Qena - Quseir road. The upper member of the Nubia Formation consists of dark brown to dark reddish brown, very fine-grained sandstone, sandy siltstone and shale. The member is commonly iron stained and locally exhibits well- developed ripple marks. It is overlain by the variegated shales of the Quseir Formation. Its thickness ranges between 15 m and 30 m in sections along both the Qena - Safaga and Qena - Quseir roads. The lower and middle members of the Nubia Formation consist of predominantly fluvial sediments deposited across a wide alluvial plain. Ward and McDonald, [6] emphasized that the upper member consists of coastal plain and delta plain deposits which grade upward into the coastal and near shore marine deposits of the Quseir Formation. The Nubia/Quseir contact marks the transition from subaerial to shallow marine deposition as the Tethys Sea transgressed southward across the continental platform.

RESULTS

Petrography: The studied sandstones of the Nubia Formation are creamish yellowish white to light brown, semi-friable and massive. The framework grains are monocrystalline quartz (Qm), polycrystalline quartz (Qp), K-feldspars (KF), plagioclase feldspars (PF) and lithic fragments (L) (Table 1). The estimated average modal composition (quartz-feldspar–lithic fragment: QFL) ratio is $Q_{942}F_{1,3}L_{4,5}$. Based on The Dott-McBride [15, 16] scheme these sandstones are classified as quartz arenites and quartz wackes (Fig. 3); the later were recorded only in the lower most layers of sections QSF I and QQS I close to the Basement Complex.

The quartz grains are medium to fine-grained, moderately well- sorted and rounded to subrounded (Fig. 4a). The matrix and cement constitute about 9.8% of the rock. The former consists mainly of clay minerals and other detrital components where as cements are represented by clays, silica overgrowths, iron oxides and dolomite (Fig. 4b-4c). The Rock fragments are made up mainly from clay and chert (Fig. 4d). The identified Heavy minerals species are zircon, rutile, tourmaline and mica flakes were occasionally recorded (Table 1).

Authigenic Minerals: The most common authigenic mineral constituents of the studied Nubian sandstones are quartz, feldspar, kaolinite, illite, iron oxides and carbonates.

Authigenic quartz exists in all samples under investigation and is better developed in those having large original intergranular pores. Authigenic quartz forms about 0.3 to 1.5% of the rocks (average 0.5%). Quartz overgrowth with euhedral faces are common (Fig. 4e). Evidently, overgrowths were formed prior to carbonate cementation at a very early stage of diagenesis (Fig. 4f). Formation of quartz overgrowths requires acidic or slightly alkaline pore waters and an environment containing sufficient dissolved silica, such as that results from dissolution of feldspars and lithic fragments and/or kaolinitization [17, 18].

Authigenic feldspars are less abundant than authigenic quartz. Authigenic feldspars (Fig. 5a), they exist as prismatic as rhombohedral crystals microcline, that were formed almost as a result of overgrowths on detrital grains in sandstones. Authigenic feldspars occur also as pore- fillings, locally forming from late stage authigenic illite (Fig. 5a).

The growth of authigenic K-feldspars in sedimentary deposits requires that the diagenetic environment is riched in K, Al and Si ions [19]. These ions could be released by the dissolution of detrital alkali feldspars and other silicate framework grains by the action of alkaline interstitial solutions. The chemical conditions required for the precipitation of authigenic feldspars are controlled by the Ph and the proportions of K, Na, Ca and Si. It is likely that the authigenic feldspars in the studied Nubian sandstone were formed at low temperatures and shallow depths of burial.

The Authigenic Clay Minerals: Authigenic kaolinite was recorded in all the studied samples. Occurring as well crystallized pore fillings and linings that were precipitated from solutions as they show no evidence of alteration from a clay mineral precursor. Previous studies emphasized that The formation of authigenic kaolinite requires: (i) pore waters of acidic nature; (ii) sufficient porosity and permeability to allow migration of pore waters and to provide growth space; (iii) the presence of K-feldspar and/or muscovite that represent a source of Al and Si. Kaolinite consists of pseudo hexagonal plates growing between detrital grains and exhibiting bridges (Figs. 5b-5c).

Authigenic illite was occasionally recorded in the studied sandstones. It occurs as pore-linings grains –coating commonly have hair- like forms is common. Also, curled exist flakes-like of illite that is commonly curled is also oriented perpendicular to quartz grain surfaces. Morad *et al.* [20] reported that authegenic illite, typically forms from K-rich solutions during progressive burial under elevated temperature (90°-130°).



Fig. 3: QFL triangular diagram shows the classification of the Nubia sandstones, modified from Dott [15] and McBride [16]

							Detrital grains%																
		S No.	Av. grain size	Grain e roundness	s Sorting	Grain	Quartz		Feldspars		Lithic fragments			Heavy minerals			Authigenic cement %						
Location							Qm	Qp	PF	KF	Lp 1	Ls	Mica	 ι Ор	Nop	Clays	Qz th	F th	Cal	Dol	I.O	ill	Ka
Qena -Safaga	Sectin QSF I	1	F-VC	SA-SR	Ps-Ms	P > L	28	40	0.3	0.7	3	1.	0.2	0.3	0.1	2.3	0.6	0.1	3	18.3	0.7	0.7	0.2
road		2	F-VC	SA-SR	Ps-Ms	P > L	34	39	0.2	1.2	2.7	1.	0.1	0.3	0.1	2.3	0.4	0.2	4.5	11.5	0.6	0.8	0.3
		3	F-VC	SA-SR	Ps	P > L	33	43	0	1.1	2.8	1.	6 0.1	0.4	0.3	3.2	1.5	0	3	8.5	0.9	0.5	0.1
		4	M-VC	SA-SR	Ps-Ms	$\mathbf{C} > \mathbf{P}$	38	40	0.5	0.7	3.1	2.	0	0.3	0.2	1.2	1.1	0.1	4.7	6	0.6	0.8	0.3
		5	F-VC	SA-SR	Ps-Ms	P > L	40	39	0.3	0.8	2.8	2.	0	0.5	0.3	1.1	0.3	0.1	4	6	1	0.9	0.3
		6	F-C	SA-R	Ms	P > L	44	37	0.2	0.9	1.9	2.	5 0	0.5	0.4	1.2	0.8	0.1	3.8	4.8	1	0.6	0.2
	Sectin QSF II	1	VF-M	SR-R	Ms	P > L	67	22	0.2	0.8	2.9	2.	0	0.4	0.2	1.1	0.3	0	0	0.8	0.9	0.6	0.1
		2	VF-M	SR-R	Ms	P > L	66	21	0.2	0.7	2	2.	5 0	0.5	0.3	1.3	0.3	0.1	0.8	2.1	1	0.9	0.3
		3	VF-M	R	Ms-Ws	$\mathbf{C} > \mathbf{P}$	69	20	0	0.8	2.2	2.	6 0	0.6	0.3	1.2	0.3	0.2	0.6	0.8	1.2	0.4	0.1
		4	F-M	R	Ms-Ws	$\mathbf{P} > \mathbf{\Gamma}$	71	18	0.3	0.6	2.4	2	0	0.6	0.4	1.2	0.4	0.1	0.5	0.6	1.2	0.5	0.2
		5	F-M	SR-R	Ms	$\mathbf{P} > \mathbf{\Gamma}$	70	18	0.3	0.7	2.5	1.	0 (0.4	0.2	1.1	0.3	0.2	1.2	1.9	0.8	0.4	0.1
		6	М	SR-R	Ms	F > P	73	17	0.2	0.7	2.8	1.	0	0.4	0.1	0.9	0.9	0	0.4	1	0.9	0	0
Qena -Quseir	Sectin QQS I	1	F-VC	SA-SR	Ps-Ms	$\mathbf{C} > \mathbf{P}$	24	50	0.3	0.8	1.8	0.	0.3	0.4	0.2	2.4	0.3	0	5.3	11.9	0.9	0.5	0.2
road		2	F-VC	SA-SR	Ps-Ms	$\mathbf{C} > \mathbf{P}$	28	49	0.1	1.4	1.6	0.	0.2	0.4	0.4	2.3	0.6	0.2	4.8	8.8	0.8	0.4	0.2
		3	F-C	SA-SR	Ps-Ms	$\mathbf{P} > \mathbf{\Gamma}$	32	49	0.4	1.1	1.5	1	0.1	0.3	0.2	1.3	0.3	0	4.1	6.6	0.6	1.1	0.4
		4	F-VC	SA-SR	Ps-Ms	P > L	34	46	0.4	1.1	2	1.	0	0.6	0.4	1.2	0.4	0	3.8	6.5	1.2	0.7	0.3
		5	F-VC	SA-R	Ms	C > P	35	47	0.1	1.3	1.6	1.	0	0.5	0.3	1.3	0.6	0.1	3.9	4.9	1	0.5	0.2
		6	F-C	SA-R	Ms	P > L	40	44	0.4	0.9	1.7	1.	8 0	0.4	0.3	1.2	0.5	0.2	2.2	4.8	0.8	0.5	0.3
	Sectin QQS II	1	VF-M	SR-R	Ms	$\mathbf{P} > \mathbf{\Gamma}$	65	22	0.1	0.8	1.8	1.	5 0	0.6	0.4	1.9	0.3	0.1	1.9	1.6	1.2	0.5	0.2
		2	VF-M	SR-R	Ms	F > P	66	20	0.1	0.9	2.1	1.	0	0.5	0.4	1.7	0.3	0.2	2.3	2.9	1	0.2	0
		3	F-M	SR-R	Ms	P > L	68	19	0.2	0.8	2.1	1.	6 0	0.8	0.6	1.5	0.4	0	2	1.3	1.6	0.4	0
		4	F-M	SR-R	Ms	P > L	68	19	0.2	0.9	2.4	1.	0	0.7	0.4	1.2	0.4	0	1.3	1.7	1.4	0.9	0.4
		5	F-M	R	Ms-Ws	P > L	72	16	0.2	0.8	2.5	2	0	0.3	0.2	1.3	0.3	0.1	1.5	1.3	0.6	0.7	0.2
		6	М	R	Ms-Ws	P > L	72	16	0.3	0.8	1.6	0.	0 0	0.4	0.2	1.1	0.4	0.2	2	2.2	0.9	0.8	0.2
Average							51.5	31.3	0.23	0.89	2.24	1.	2 0.04	0.46	0.29	1.52	0.5	0.1	2.57	4.87	0.95	0.6	0.2

F-VC = fine to very coarse; F-C = fine to coarse; M-VC = medium to very coarse; M-C = medium to coarse; SA-SR = Subangular to subrounded; SA-R = subangular to rounded; SR-R = subrounded to rounded; Ps= poorly sorted; M-Ps= moderate to poorly sorted; Ms= moderately sorted; Monocrystalline quartz (Qm); Polycrystalline quartz (Qp); K- feldspar (KF); Plagioclase -feldspar (PF); Plutonic lithic fragment (Lp); Sedimentary lithic fragment (Ls); Mica (M); Heavy minerals (Hm); Opaque (Op); Non-Opaque (NOp); Qt= total Quartz; F= Feldspar; Lt = Total Lithic fragment. Qt = Qm + Qp, F = Pl + KF, L = Lp + Ls, Lt = L + Qp.

The Iron Oxides Cements: Iron oxides occur in the studied sandstones grain coating and less commonly filling or lining the pore spaces as a cement coating around detrital grains and to lesser extent as patches between framework grains filling pore spaces (Figs. 5d and 5e). Authigenic goethite exists mainly along the cross bedding planes in the most upper layers of the studied

sections. It occurs mainly as a pore- fillings, partially replacing feldspars and muscovite grain. Authigenic botroydal goethite was recorded coating quartz overgrowths (Fig. 5e). Also it forms spherical concretions having relatively thick internal growth bands that are roughly concentric. These bands represent zones of different intensity of denser cementation by iron oxides.



Fig. 4: SEM and Photomicrographs showing: a) Quartz grains are medium- to fine-grained, rounded to subrounded and are moderately well sorted (Note, point (Pc), line (Lc) and concave-convex (C-Cc) contact between quartz grains);
b) Quartz overgrowths (QO) engulfed by dolomite cement (D) (Note, leached dolomite cement (Dd); c) Authigenic kaolinite booklets (K); d) Plutonic (granite) rock fragment (LF) (Note, Quartz grains and rock fragments show multiple deformation fractures (Fr)); e) Quartz overgrowths (QO) corroded (QC) and engulfed by dolomite cement (D); f) Quartz overgrowth with euhedral faces.

Hematite cements occur as pore- fillings cement, it ranges from 0.6 to 1.6% (Table 1). Hematite shows both botryoidal and cellular textures. It is present in the form of pore-lining and interstitial matrix (Fig. 5e), hematite in the form acicular crystals, fringing the pore spaces and coating detrital quartz a very common in the most upper layers of the studied sections. Also, is elongate laths that coat quartz overgrowths the grain surface are common (Fig. 5e).

The iron oxides that formed cements might have been derived from iron – rich minerals as a result of weathering under an oxidizing conditions mostly during the uplifting stage of diagenesis (epigenesis). The iron precipitates as hematite and/or goethite that subsequently changed to hematite.

Carbonate Cements: Carbonates are the second most abundant cements in the studied sandstones. They form 4.5% to 20.1% (average of 2.8%) of the rocks and consist of dolomite and less commonly ferroan and nonferroan calcite. Dolomite occurs mainly as coarse crystal where as ferroan dolomite exists as micro to moderately crystalline rhombs filling pores (Fig. 5f) and/or a grain replacive phase (Fig. 5f). The spread wide ferroan carbonate cementation seems to have occurred by alkaline pore water under reducing conditions [21, 22].

Slightly ferroan calcite cements form about 0 to 8% (average 2.5%) in the studied sandstones, they exist as poikilotopic and sparitic crystals displacing a patchy distribution or corroding and fracturing quartz grains (Fig. 5f). The ferroan calcite cement has survived dolomitization most probably due to the poor permeability of the sandstones for the circulation of Mg-rich fluids. The abundance of large oversize pores, floating grains and corroded and etched quartz grains suggest that calcite cements were once much more abundant but were later dissolved.

Diagenetic Processes: The studied Nubian sandstones were affected by several diagenetic processes. These include (i) compaction, (ii) mechanical infiltration of clays, (iii) cementation, (iv) replacement, (v) alteration and (vi) dissolution oxidation of iron oxides.

Compaction: The studied sandstones were subjected to compaction during its progressive burial as evidenced by the presence of various type of pressure-solution grain (Fig. 4a). The point and straight contacts average 68% and 19%, respectively. Where as concavo-convex contacts average 2.1% this strongly suggest a limited pressure solution activity mostly as a result of presence of a primary pore-filling matrix (Fig. 5f).

World Appl. Sci. J., 36 (6): 789-798, 2018



Fig. 5: SEM and photomicrographs of the studied Nubian sandstones showing: a) dissolution of K-feldspar (Kf) grain a part of which was altered to illite; b) authigenic kaolinite (K) and illite formed by alteration of K-feldspars (Kf);
c) authigenic kaolinite (K) in the form of booklets and vermicular aggregates filling intergranular pores and coating detrital grains; d) detrital quartz (Q) and feldspar grains and feldspar grains same of which have overgrowths quartz (QO), detrital feldspars (Kf) and authigenic feldspars (FO) are coated and engulfed by dolomite cement; e) botryoidal goethite (Ge) coating the detrital and authigenic quartz grains, while laths of elongate shape of hematite (He) coating the authigenic quartz (QO); f) fractured and strained detrital quartz grains (Fr) by calcite (Ca) showing evidence of late stage cemented and partially corroded dissolution (Cd).

Mechanical Infiltration of Clays: Mechanical infiltration of clays represents the earliest diagenetic process, particularly those of the lowest part of sections QSF I and QQS I. The use of SEM made it easy distinguish to these clays from those of authigenic origin. The mechanically infiltrated clay exist as pore-fillings and grain coatings. They occurring the form of platelet oriented parallel to the grain surface (Figs. 5b-5c). The fact that the infiltrated clays exist only in the lower most part of the Nubian sandstones succession strongly suggests that the underlying soil horizon might have served as a supply for clay.

Cementation

Authigenic Quartz: Cementation with silica is a common diagenetic feature in the studied sandstones (Figs. 4e-4f; 5d-5e-6a). In most cases, it is represented by quartz overgrowths which resulted in the development of euhedral crystals. This is probably due to the relatively high permeability of sandstones and ease of percolation of water and silica- rich fluids [23]. It is most likely that the dissolution of feldspars and siliceous rock fragments played the major role in providing this silica.

Feldspar Overgrowth: Authigensis of feldspars was an early diagenetic process that predated any tectonic deformation as well as locally forming from dolomite cementation [24] (Figs. 5a and 5d).

Carbonate Cementation: The chemistry of the interstitial fluid turned gradually alkaline, so the authigenic carbonate started to precipitate accompanied by the major part of the silica overgrowths and to a lesser extent, parts of the detrital quartz grains were corroded and partially dissolved (Fig. 4f). The abundance of large, oversize pores, floating grains, corroded and etched quartz grains in the Nubia sandstones suggest that calcite cement was once much more abundant but was subsequently dissolved 6b). Petrographic (Fig. examination and SEM indicate two generations of calcite cements. The first is that of the non- ferroan calcite which took place at a very early stage of diagenesis and hindered the complete filling of the intergranular pores. The second is that of ferroan calcite which post dated the formation of quartz overgrowths and thus, occurred during a very late stage of diagenesis.



Fig. 6: Photomicrographs showing: a) a large vug and intergranular pores developed as a result of significant dissolution of detrital and authigenic grains; b) pore filling iron oxide cement engulfed by authigenic calcite (Ca) and dolomite cements, indicating a large stage of carbonate cementation; c) detrital and authigenic quartz and feldspar grains are almost floating in an abundant late diagenetic poikilotopic and sparry calcite cement.

The presence of quartz grains corroded by dolomite suggests the syndepositional dolomite cementation, which was later partially replaced by Fe dolomite cement during deep burial. The early precipitation of carbonate cement takes place a few centimeters below the sediment– water interface [25]. This type of cementation occurs by the exchange of interstitial marine pore water either by meteoric water or by pore water expelled from the underlying sediments. However, the thin dark brown mosaic of Fe dolomite coating or cementing the detrital grains may be extrabasinal weathering rinds generated during deep burial [26].

Kaolinite Cementation and Illite Authigenesis: The fact that authigenic kaolinite exists as both pore- fillings and linings (Figs. 4c; 5b-5c) strongly suggests that postdated the quartz overgrowth phase and predated dolomite cementation [18]. Mostly, it was precipitated from interstitial pore waters or formed by alteration of minerals by substantial acid water flux [27].

Authigenic illite was formed during two diagenetic stages occurs mainly as pore-lining that coats detrital grains. The first was an early stage that preceded the formation of authigenic K-feldspar (Fig. 5c) where as the second stage post- dated this process involved the alteration of K-feldspar (Figs. 5a-5b).

Iron Oxides Cementation: Hematite and goethite cements predated carbonate cementation (Fig. 5e). Hematite cements show more than one phase of generation in many samples which suggests the persistence of reddening for a long time.

Replacement: Some quartz and feldspar grains were corroded and replaced by Fe-dolomite (Figs 4b; 4f; 5f). Also, Ferroan dolomite replaced some detrital clays of the

matrix. Generally, the studied sandstones do not show evidence of pressure solution of grains. Early carbonate cement might have acted as a buffer between the framework quartz grains and thereby ceased grain- tograin stress. This may explain the intergranular pressure solution effects why did not develop even under burial conditions. Evidencely, the replacement of early silica cement by dolomite may have resulted in the retention of the original intergranular porosity (Figs 4b; 4f; 5f).

Clay replacement is very common in individual mineral grains and rock fragments. Clay replacement is not confined to detrital grains, but is also present in authigenic K-feldspar.

Alteration: Petrographic observations indicate that most of the remnants are strongly altered. Authigenic kaolinite and illite formed by alteration of K-feldspars (Figs. 5a and 5b).

Dissolution, Oxidation of Iron Oxide: The dissolution of detrital grains and authigenic minerals in the Nubia sandstones produce secondary (vuggy) porosity (Fig. 6a). The metastable and unstable heavy minerals such as pyroxenes and amphiboles were partially or completely dissolved which resulted in the increase in proportion of the ultrastable grains such as are represented by zircon, rutile and tourmaline. The dissolution of feldspars in the Nubia sandstone is a crucial feature. K-feldspar grains that were etched by dissolution are very common. In general, the dissolution took place preferentially along the cleavage plane of the grains (Fig. 5a). Dissolution included not only the detrital k- feldspar grains, but also authigenic ones. The released K, Al and Si ions essential responsible for the formation of authigenic illite (Fig. 5a). Also, dissolution of K-feldspar carbonate and some heavy minerals were

responsible for the development of much secondary pores (Figs. 4b; 5f). It is most likely that dissolution culminated during the shallow or intermediate burial stages of diagenesis.

The precipitation of secondary silica was accompanied and most probably succeeded by partial or complete dissolution of the carbonate fragments. The presence of quartz overgrowth and dolomite rims maintained preservation of the oversize pores left after the dissolution of the carbonate fragments (Fig. 6a).

The Diagenetic History: The diagenetic history of Nubian sandstones consists of four stages:

The Eodiagenetic Stage: This stage includes changes that took place soon after the sediments were deposited. It comprised their cementation with poikilotopic calcite and quartz overgrowths (Figs. 4b, 4e, 4f, 5d; 6c) as well as minor dissolution of unstable grains such as feldspars and overgrowth on quartz grains continued to the late diagenetic stage in sediments with no or little carbonate cement. During early diagenetic stage, some feldspar grains altered to authigenic kaolinite (Fig. 5b).

The Immature Mesodiagenetic Stage: This stage includes changes that resulted from mechanical compaction. The progressive burial was accompanied by mechanical compaction and infiltration of clays that led to reduction in pore spaces. Compaction is documented by fracturing of detrital quartz, bending of muscovite grains and the development of concavo-convex contacts between grains (Fig. 4a). It continued to the late stage of diagenesis in sandstones with little carbonate cement but was less effective.

The Mature Mesodiagenetic Stage: This stage involved the production of considerable secondary porosity. As a result of extensive dissolution of the unstable grains such as those of feldspars and rock fragments. The circulating acidic waters precipitated secondary silica as overgrowth on quartz and feldspars grains (Figs. 4b; 5d; 6a) and resulted in the partial or complete dissolution carbonate cements. The later is indicated by the presence of well preserved oversize pores (Fig. 6a).

The Telodiagenetic Stage: This late diagenetic stage included all changes that took place after the stage. Marine transgressions produced significant changes in the Ph of the circulating subsurface solutions. They became more alkaline which led to silica dissolution, carbonate cementation and replacement processes.

CONCLUSIONS

Four exposed stratigraphic sections along the Qena - Safaga and Oena - Ouseir roads were sampled, described and measured in detail in order to determine the detrital and the authigenic composition and diagenetic history of the Upper Cretaceous Nubian sandstones (Nubia Formation) in the central Eastern Desert of Egypt. The Nubian sandstone samples are abundant in quartz content with lower feldspar and lithic fragments. Their average modal composition $(Q_{942}F_{13}L_{45})$, classifies them as quartz arenites with subordinate quartz wackes. A variety of diagenetic aspects affected the original composition of the Nubia sandstones. The main diagenetic features include (i) compaction, (ii) mechanical infiltration of clays, (iii) cementation, (iv) replacement, (v) alteration and (vi) dissolution oxidation of iron oxides.

history of Nubia sandstones The diagenetic includes four stages. Eodiagenetic is the first stage, in which poikilotopic calcite cement, quartz overgrowths and minor dissolution of unstable grains (feldspars) took place. The second immature mesodiagenetic stage includes changes that took place due to mechanical compaction. The third mature mesodiagenetic stage includes dissolution of the remaining unstable grains (feldspar and rock fragments) and partial or complete dissolution of the carbonate fragments. The end telodiagenetic stage includes silica dissolution, carbonate cementation and grain replacement started slightly later than quartz cementation. The dissolution of unstable grains and carbonate fragments, during mature mesodiagenetic stage, increase the secondary porosity and greatly enhance the petrophysical properties of the Nubia sandstones

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