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# CLAY MINERALOGY OF THE NUBIA FORMATION, WESTERN DESERT (EGYPT)

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**Abstract:** The term Nubia Formation has been used in a broad range of stratigraphic and sedimentological connotations to designate terrestrial sandstone of Paleozoic to Mesozoic age in Egypt. The Nubia Formation is the oldest exposed rock unit and forms the basal part of the scarp face and the floor of Kharga and Dakhla Depressions. It is overlain by the Qusseir Shale Formation. The Nubia Formation in the studied locality is composed of very thick sandstone intervals intercalated with several thin shale intervals. Bulk samples are composed of clay minerals and quartz with traces of feldspars. Clay fractions separated from the different intervals of the Nubia Formation are dominated by kaolinite, smectite, and illite. Kaolinite is the major constituent in all samples. Smectite represents a major constituent in the shale intervals while it occurs as traces in the sandstone intervals. Illite occurs as traces in some samples. Clay minerals are classified into three assemblages. Based on X-ray and Scanning Electron Microscope analyses, the studied kaolinite is classified into two types. Authigenic kaolinite forms highly crystalline pore-filling books of stacked hexagonal flakes and occurs between quartz grains in the sandstone intervals while detrital kaolinite of lower crystallinity associates smectite and illite in the shale intervals. In the shale intervals occurrence of smectite as poorly crystalline flakes of unclear outlines is suggestive of detrital origin. Authigenic kaolinite formed during diagenesis of the Nubia Sandstone as a result of complete or partial dissolution or replacement of detrital feldspar grains. Abundance of detrital smectite in the shales intervals suggests their formation under arid or semiarid climatic conditions.

**Key words:** Egypt, Nubia Formation, diagenesis, kaolinite, smectite, illite.

## Introduction

The term Nubia Formation has been used in a broad range of stratigraphic and sedimentological connotations to designate terrestrial sandstone of Paleozoic to Mesozoic age in Egypt (Snavely 1984). The Nubia Formation was first introduced to the Egyptian stratigraphy by Russegger (1838 cited in Said 1962) to designate the brownish, highly dissected and almost horizontal sandstone beds, which are widely distributed over the southern parts of Egypt and Nubia in particular (Said 1962). Later, this term was used to designate any nonfossiliferous sandstone in the entire Paleozoic or Mesozoic succession. The Nubia Formation rests unconformably on the granitic and metamorphic basement complex and is overlain by the Qusseir Shale Formation.

Clay minerals formation results, either directly or indirectly, from the hydrolytic decomposition of primary aluminosilicates. The rate of hydrolytic decomposition processes is strongly affected by the rate of vertical water movement through the medium, in other words, by leaching. Under otherwise equal circumstances, higher leaching rates will produce more clay-sized material, and clay minerals belonging to more advanced weathering stages (Jackson 1965). The principal factor determining leaching rate and clay mineral composition may be the intensity of rainfall (Singer 1984). Singer (1980) found a strong negative correlation between montmorillonite in the clay fractions of soils formed from Pleistocene basalt and rate of rainfall. In the tropics, where leaching and chemical weathering are intense, there is a conspicuous abundance of the kaolinite group minerals and gibbsite near continental masses (Biscaye 1965; Zimmerman 1977).

The bulk of the geological literature on sandstones gives indication of their content of authigenic clay minerals (Wilson & Pittman 1977). Füchtbauer & Müller (1970) described sequences of diagenetic alterations, which affect sandstones of various composition under differing geochemical conditions. Clay neoformation and replacement of detrital grains are typical in many of these sequences. Millot (1970) claimed kaolinite is a common diagenetic product in the sandstones. Extensive referencing of the Russian literature by Sarkisyan (1972) suggested that authigenic clays are common in many Mesozoic and Paleozoic sandstones of various sedimentary basins in Russia. Carrigy & Mellon (1964) and Carrigy (1971) concluded that authigenic kaolinite is abundant and widely distributed in sandstones of divergent conditions and depositional environments. Wilson & Pittman (1977) listed several criteria to distinguish authigenic clays. These criteria include, the composition, morphology, distribution, and crystallinity of these clays.

The use of clays in sediments to interpret climate change was pioneered by Robert & Chamley (1987, 1991). More recently, Robert & Kennett (1992) related the abundance of smectite (70–100 %) in the early Tertiary off Antarctica to indicate arid and seasonal climates. In contrast, the occurrence of kaolinite is interpreted by Robert & Kennett (1992) to indicate high rainfall with warm temperature. In a subsequent paper Robert & Kennett (1994) concentrated on the details of $\delta^{18}O$ changes and clay mineralogy. Kaolinite increased dramatically at the Paleocene-Eocene boundary, indicating a major increase in temperature and/or precipitation (Robert & Maillot 1990). Thiry (2000) pointed out that clay minerals in sediments can be useful indicators of paleoclimatic conditions.

The petroleum potential of the Nubia Beds is being investigated actively at present (Klitsch et al. 1979). This interest, as well as other research activity on the ground water, paleontology, and sedimentology of Nubia (Klitsch 1978), has recently led to a better grasp of the stratigraphy and depositional setting. Our purpose in this paper is to shed light on the nature and origin of the clay minerals separated from samples of the Nubia Formation.

## Location and geological setting

The Abu-Tartur plateau lies 600 km to the southwest of Cairo, in the Western Desert. It is located between the Dakhla Oasis to the west and Kharga Oasis to the east. The southern edge of the plateau overlooks the Nubia plain to the south, whereas it gently tilts northward forming the general surface of the north Western Desert. Elevations on the surface of the plateau vary from 540 m to 570 m above sea level. In the northern and western parts of the area, the plateau surface is covered by limestone of the Eocene Garra Formation, which forms the higher step making the main limestone plateau. Eastward and southward, the plateau surface is highly dissected. The studied section is located approximately 20 km to the north of the Kharga-Dakhla route within the Abu-Tartur Mine (Fig. 1). The Nubia Formation in the studied area is composed of thick sandstone intervals separated by several thin shale intervals (Fig. 2). It is overlain by varicoloured shales of the Qusseir Formation. The basal part of the Nubia Formation is not exposed.

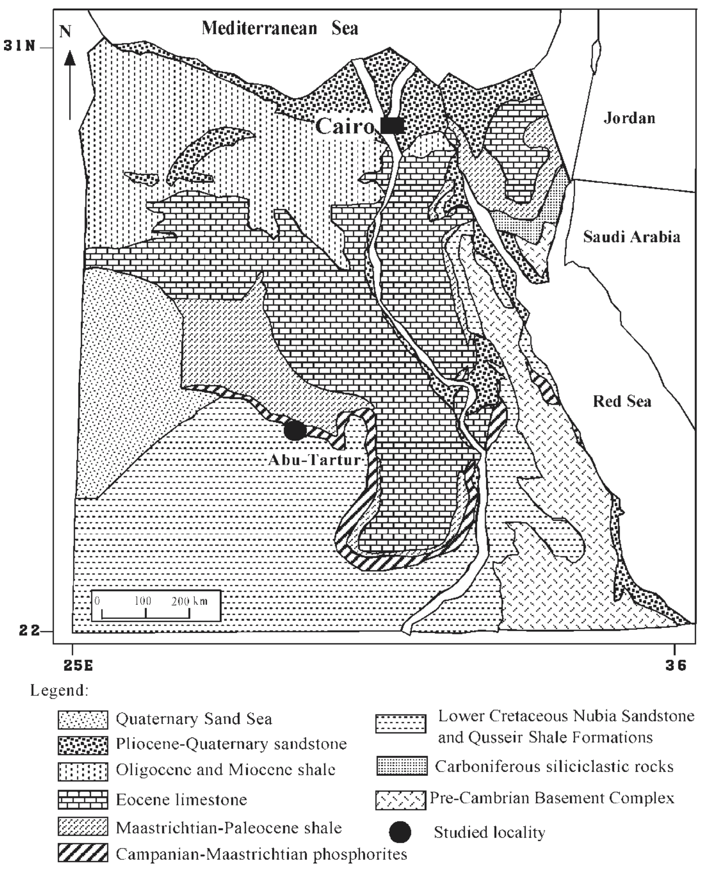


**Fig. 1.** Geological map of Egypt with the localities of the studied area (modified from Spanderashvilli & Mansour 1979).

## Materials and methods

A total of 38 samples representing the different lithological units of the Nubia Formation were collected in order to examine the possible variation in mineralogical composition especially clay minerals.

Separation of clay fraction (<2 μm) was carried out to examine the clay mineral composition of shales and their temporal and spatial variations. Approximately ten grams of shale samples were transferred to a 600 ml beaker and treated with dilute 1 N acetic acid to remove carbonates. After no more effervescence with acid, the residue was washed with distilled water and then treated with 30% $H_2O_2$ to remove organic matter. After the sample was completely disaggregated, it was washed with distilled water several times in order to reach a complete suspension. The suspended clay fraction (<2 μm) was mounted on glass slides by dropper and left to dry. For each sample, three oriented slides were prepared by the same method and with the same thickness. One is untreated, another is saturated with ethylene glycol vapor at 60 °C for one hour, and the other is heated at 550 °C for three hours.

A Philips PW 1730 X-ray generator with Ni-filtered Cu K$\alpha$ run at 40 kV and 25 mA was used to examine both the bulk samples and clay fractions. Bulk samples were analysed by the X-ray technique after grinding in an agate mortar and mounting in the sample holder. The scans were limited to the 2θ 2° to 80° range. The clay fractions were analysed using the X-ray technique. The scans were limited to the 2θ range from 2° to 40°. Smectite was identified by the peak at 1.4 nm that is expanded to 1.7 nm after glycolation and reduced to 1.0 nm by heating (Moore & Reynolds 1997). Kaolinite was identified by the peak at 0.7 nm, which is not affected by glycolation, and disappeared by heating at 550 °C for 3 hours (Moore & Reynolds 1997). Illite was identified by the peak at 1.0 nm, which is not affected either by glycolation or by heating (Moore & Reynolds 1997). Clay minerals abundance is estimated using the peak area of the first basal reflections, without using any correction factor.

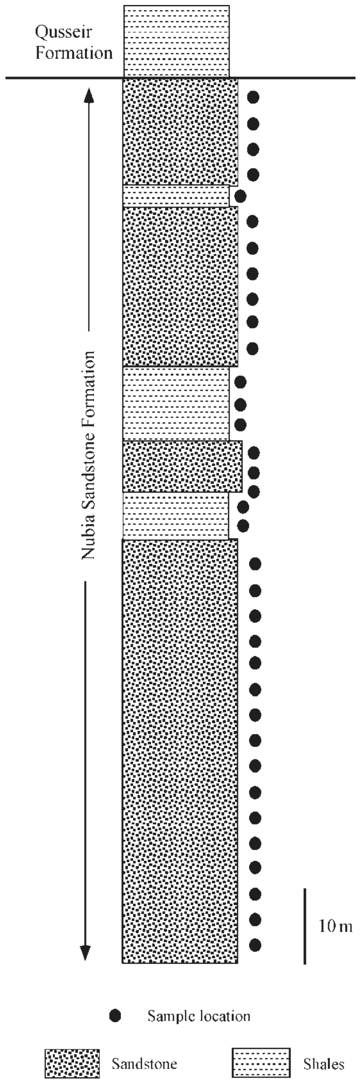


**Fig. 2.** A detailed lithostratigraphic section of the Nubia Sandstone Formation in the Abu-Tartur area, Western Desert, Egypt.

Five selected samples were observed on a fractured surface under Scanning Electron Microscope (SEM) (Philips S-2400s) at the Geological Survey of Egypt to examine the morphology of clay minerals.

## Results

### *Petrology and Petrography*

The Nubia Formation in the studied area is classified into several thick sandstone intervals separated by several thin shale intervals (Fig. 2). The sandstone intervals are composed of 40 to 20 m thick yellowish white, friable, medium- to fine-grained, cross-bedded to cross-laminated sandstone. The shale intervals are composed of 6 to 1.5 m thick of yellow, yellowish grey, hard claystone.

Under the polarizing microscope, the Nubia sandstones are composed entirely of white to pale grey, monocrystalline, subrounded to subangular, and medium- to fine-grained quartz, which are cemented by iron oxides and/or clay minerals (Fig. 3). In some instance pyroxene and zircon crystals are detected (Fig. 4 and Fig. 5 respectively). On the other hand, the shales are composed entirely of brownish grey clay minerals with some pale grey, monocrystalline, subrounded to subangular, and medium- to fine-grained quartz (Fig. 6).

### *Mineralogy*

Bulk samples are composed entirely of quartz with traces of feldspars. The X-ray data for the clay fractions separated from the different intervals of Nubia Formation are dominated by kaolinite, smectite, and illite. Kaolinite is the major constituent in all samples and its contents range from 80 to 98 % of the clay minerals, while smectite occurs as traces especially in the sandstone intervals ant its contents range from 2 to 10 % of the clay minerals. In the shale interval on the other hand it occurs as major constituent and its contents range

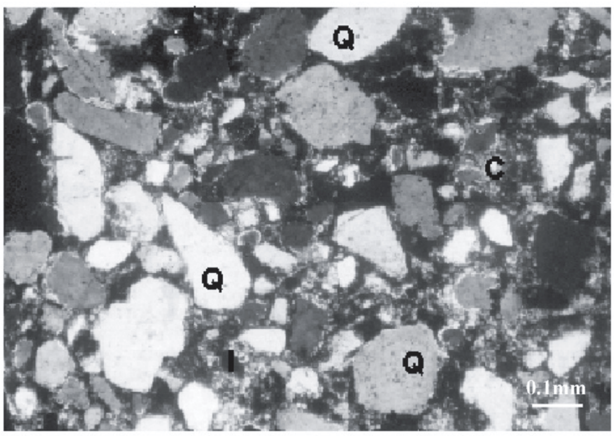


**Fig. 3.** A microscopic photograph of the Nubia Sandstone under the polarizing microscope. It is composed entirely of monocrystalline, subrounded, medium-grained detrital quartz cemented with clays and iron oxides.

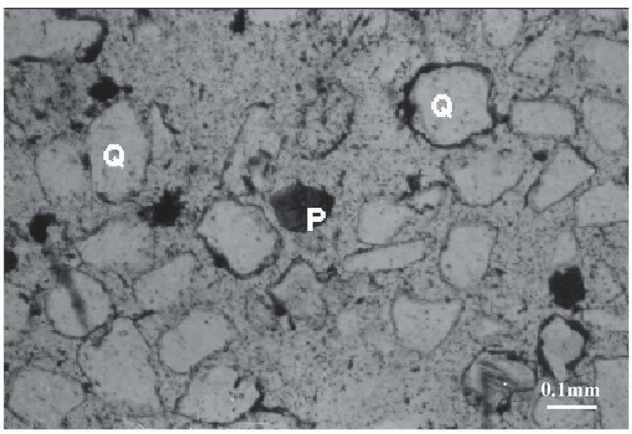


**Fig. 4.** A microscopic photograph of the Nubia Sandstone under the polarizing microscope. It is composed entirely of monocrystalline, subrounded, medium-grained detrital quartz cemented with clays and iron oxides. In some instances it contains some pyroxene crystals (P).

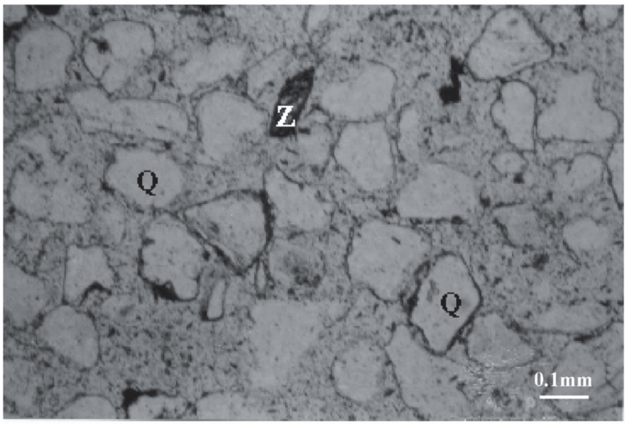


**Fig. 5.** A microscopic photograph of the Nubia Sandstone under the polarizing microscope. It is composed entirely of monocrystalline, subrounded, medium-grained detrital quartz cemented with clays and iron oxides. In some instances it contains some zircon crystals (Z).

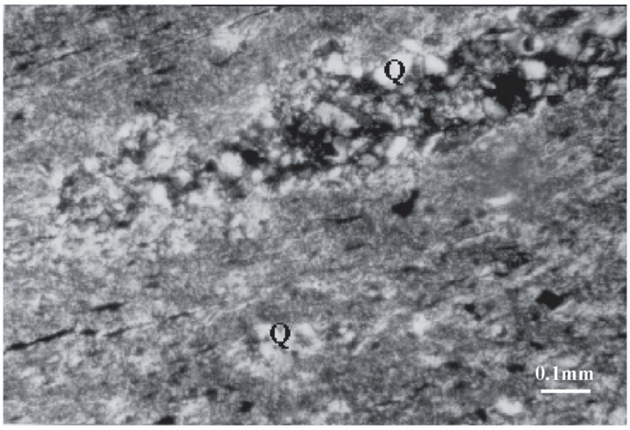


**Fig. 6.** A microscopic photograph of the shale interval under the polarizing microscope. It is composed entirely of clays with some detrital quartz grains (Q).

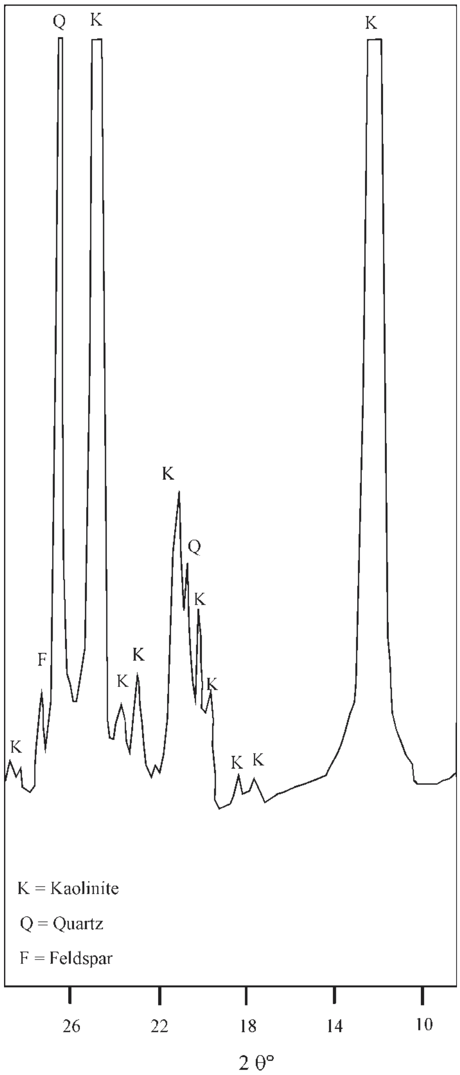


**Fig. 7.** X-ray diffraction pattern of the clay fraction separated from the sandstone intervals. It is composed of kaolinite (K) with some quartz (Q) and feldspar (F) and represents the kaolinite assemblage.

from 20 to 30 % of the clay minerals. Illite occurs as traces in all samples and its contents range from 1 to 7 % (see Fig. 10) of the clay minerals. Other minerals present are quartz and plagioclase. Representative X-ray diffraction patterns of the oriented clay aggregate of <2 μm fraction of different intervals are shown in Figures 8–10. The clay minerals are classified into three assemblages in descending order of abundance. The kaolinite assemblage (Fig. 7) characterizes most of the sandstone intervals, kaolinite-smectite assemblage (Fig. 8) characterizes some of the sandstone intervals, and kaolinite-smectite-illite assemblage (Fig. 9) characterizes the shale interval. On the basis of the X-ray data, the kaolinite is classified into two genetic types according to its degree of ordering. Well ordered authigenic kaolinite is very common in the sandstone intervals (Figs. 7–8). Detrital kaolinite characterized by a lower degree of ordering is very common in the shale intervals (Fig. 9). Higher ordering is shown by better separation of reflections in the range 2θ 2° to 25°. Semiquantitative analysis of clay minerals in the Nubia Formation is shown in Figure 10. Kaolinite contents range from 100 % to 65 % of the clay minerals. Smectite contents range from 35 % to 5 % of the clay minerals. Illite represents 4 % to 7 % of the clay minerals.

(On the term "crystallinity" see Report of the AIPEA Nomenclature Comm. For 2001: Guggenheim et al. 2002: Clays Clay Min. 50, 3, 406–409.)

### *SEM observations*

SEM micrographs of the kaolinite separated from the sandstone interval consist of pore-filling books of stacked hexagonal flake filling the space between quartz grains (Fig. 11) or coating the quartz grains (Fig. 12). Smectite occurs as flake between quartz grains (Fig. 13). Crystals of kaolinite are more or less similar to the well-formed, large crystals of clear outline of authigenic kaolinite reported by Wilson & Pittman

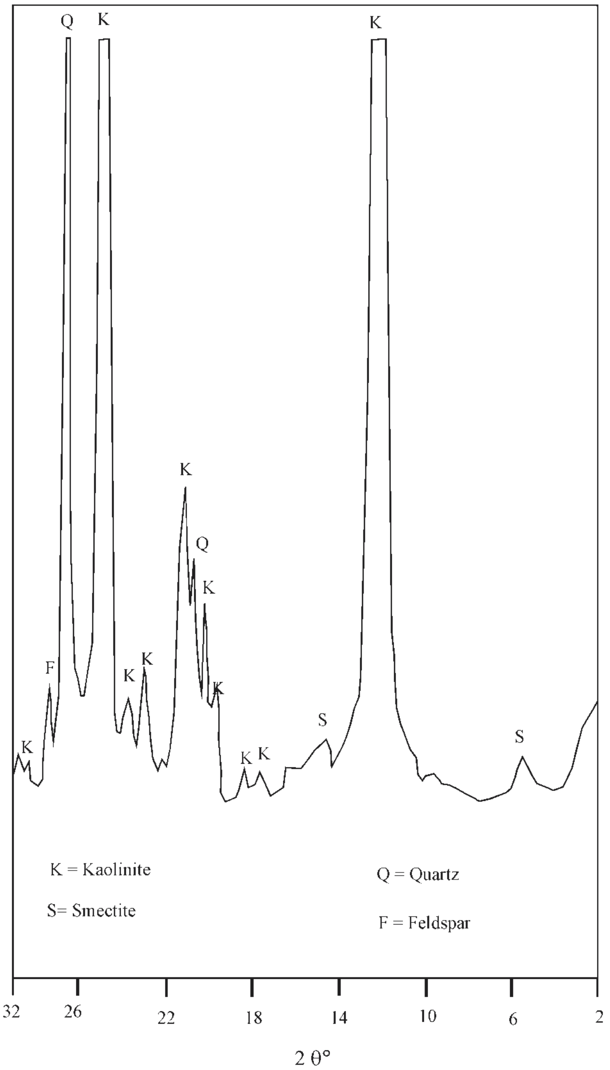


**Fig. 8.** X-ray diffraction pattern of the clay fraction separated from the sandstone intervals. It is composed of kaolinite (K) and smectite (S) with some quartz (Q) and feldspar (F) and represents the kaolinite-smectite assemblage.

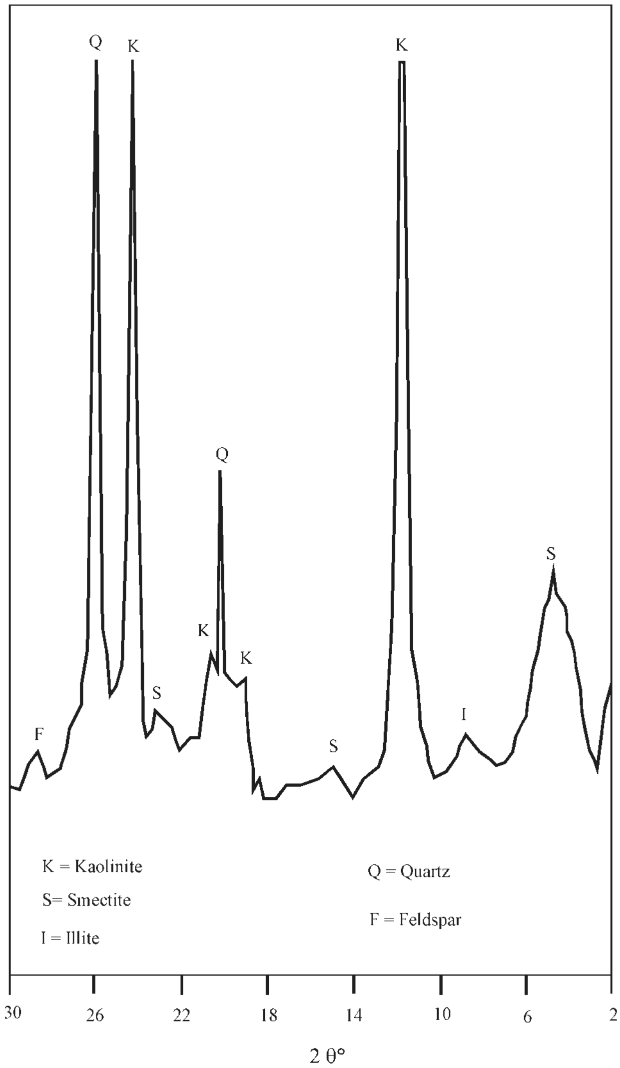


**Fig. 9.** X-ray diffraction pattern of the clay fraction separated from the shale interval. It is composed of kaolinite (K), smectite (S), and illite (I) with some quartz (Q) and feldspar (F) and represents the kaolinite-smectite-illite assemblage.

(1977) and Keller (1978), while smectite is smaller and with a less clearly defined outline compared with the well-formed, large crystals of clear outline of authigenic smectite reported by Keller (1978). Therefore the authors consider the studied kaolinite to be authigenic kaolinite while smectite is considered to be detrital in which the size and outline of the crystals are affected by transportation. This interpretation is also confirmed from the X-ray data.

## Discussion

Conditions apparently conductive to forming kaolinite at the earth's surface are well summarized by Keller (1964). As a weathering product, the presence of kaolinite implies (1) a high Al:Si ratio, (2) an acid environment, and (3) Na, Ca, K, Mg, and Fe absent or out of circulation. Dixon (1989) reviewed the origin and formation of kaolinite minerals and showed that precipitation from solution of kaolinite required acid conditions with moderate silica activity and small amounts of base cations. The fact that kaolinite is formed by aluminum silicate alteration in weathering and by diagenetic environments is clear from geological relationships (Bucke & Mankin 1971). Three major models of kaolinite formation have been suggested by Degens (1960). The basic approach involves interaction in solution between isolated species of monomeric silica and alumina, with $OH^-$ and $H^+$. A second mechanism inserts an intermediate colloidal phase from which crystallization proceeds. The third invokes structural arrangement of alumina-silica residue left from selective leaching of parent materials such as feldspars.

The occurrence of kaolinite in the sandstone intervals as pore-filling books of stacked hexagonal flake between quartz grains as observed under the SEM and its high degree of ordering as shown by the X-ray data, indicate that this kaolinite is of authigenic origin. As far as kaolinite is the main weather-

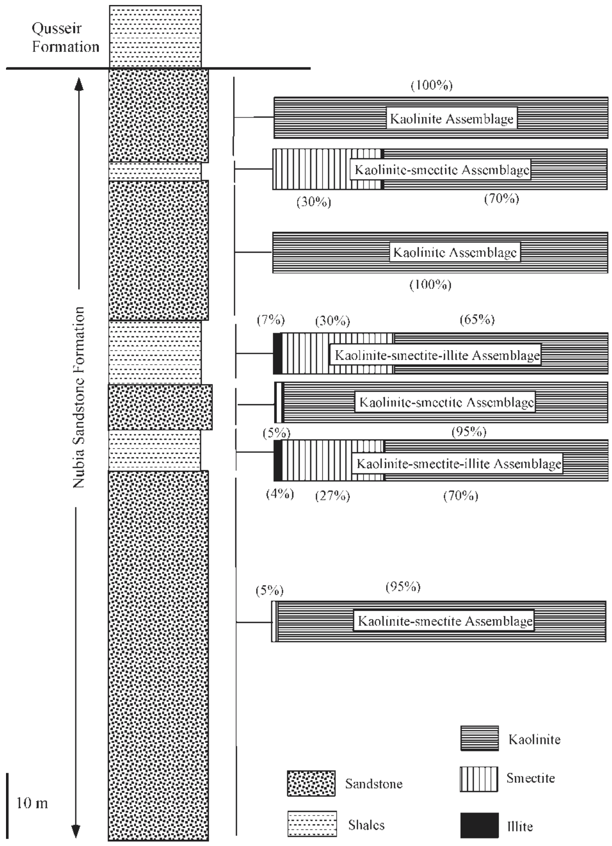


**Fig. 10.** Vertical distribution of clay minerals through the Nubia Formation. The shale intervals have higher smectite contents compared with sandstone intervals.

ing product of acidic and feldspar-rich rocks (Hay 1992 and Parrish 1998), it is suggested that the kaolinite in the Nubia Sandstone Formation was formed during diagenesis of the Nubia Sandstone as a result of complete or partial dissolution or replacement of the detrital feldspar grains which are recorded as one of the constituents of the Nubia Sandstone Formation.

Early diagenetic kaolinite results from flushing sandstones with meteoric water flow; thus maximum development of kaolinite is indicative of the proximity of shoreline, the continuity of sandstone bed, and the sea level changes (Środoń 1999). In the absence of flushing, the kaolinite + feldspar assemblage is stable until 120 °C, and then reacts forming illite. Experiments of Huang et al. (1986) confirmed the role of fluid/rock ratio in altering feldspar into kaolinite or illite. According to Osborne et al. (1994), early diagenetic kaolinite crystallizes at different temperatures with different habits: vermin-form between 25 and 50 °C and blocky between 50 and 80 °C. Late diagenetic (telogenetic) kaolinite develops in sandstones flushed by gravity-driven meteoric waters after the tectonic inversion of a basin. Accordingly, and based on the morphology of its grains, the kaolinite separated from the Nubia Sandstone Formation is considered as early diagenetic resulting from flushing sandstones with meteoric water at temperatures around 50 °C.

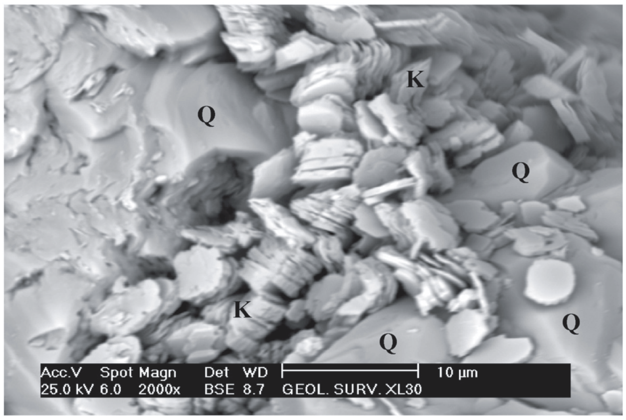


**Fig. 11.** Scanning electron micrograph of sandstone sample from the Nubia Formation. Kaolinite (K) occurs as hexagonal crystals of small and undefined outline between quartz grains (Q).

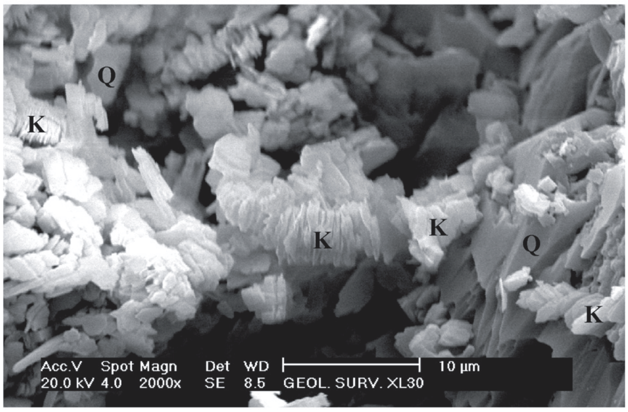


**Fig. 12.** Scanning electron micrograph of sandstone sample from the Nubia Formation. Kaolinite (K) occurs as pore-filling books of stacked hexagonal flakes between quartz grains (Q).

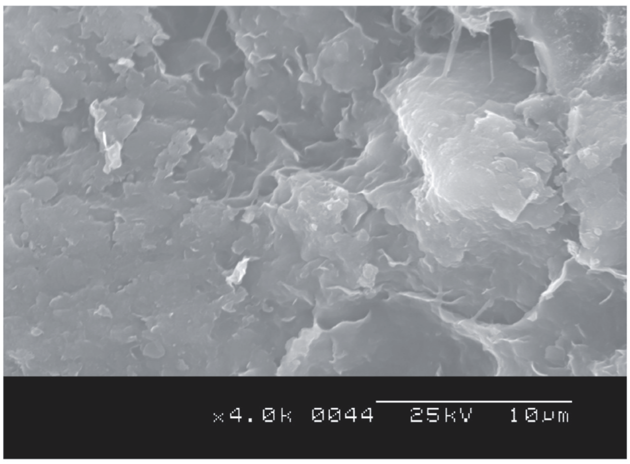


**Fig. 13.** Scanning electron micrograph of shale sample from the Nubia Formation. Smectite occurs as flakes of small and undefined outline between quartz grains.

The authigenic vs. detrital origin of smectite has been debated vigorously (Środoń 1999). On the basis of particle morphology, detrital smectite can be distinguished from authigenic smectite using morphology (Wilson & Pittman 1977). The factors that strongly influence the origin and formation of smectite as reviewed by Borchardt (1989), include low-lying topography, poor drainage and base-rich parent material, leading to favourable chemical conditions characterized by high pH, high silica activity and abundance of basic cations. Robert & Kennett (1992, 1994) related the abundance of smectite (70–100 %) in the early Tertiary off Antarctica to arid and seasonal climates.

Occurrence of smectite as low crystalline flakes of unclear outlines in the shales intervals is suggestive for detrital origin. Its abundance indicates the prevalence of arid to semiarid climate during the deposition of this shale interval. This interpretation is in agreement with the observation of Klitsch et al. (1979) based on the identification and distribution of fossil plants.

## Conclusions

1. Clay fractions separated from the different intervals of Nubia Formation are dominated by kaolinite, smectite, and illite. Kaolinite is the major constituent in all samples while smectite occurs as traces especially in the sandstone intervals. In the shale intervals smectite occurs as a major constituent. Illite occurs as traces in all samples.

2. Kaolinite is classified into two types. Authigenic kaolinite forms highly crystalline pore-filling books of stacked hexagonal flake found between quartz grains in the sandstones intervals and detrital kaolinite of low crystallinity associated with smectite in the shale intervals.

3. Authigenic kaolinite formed during diagenesis of the Nubia Sandstone as a result of complete or partial dissolution or replacement of detrital feldspar grains.

4. Smectite is of detrital origin and its abundance in the shale intervals suggests its formation under arid or semiarid climatic conditions.

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