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PALYGORSKITE IN THE EOCENE ROCKS OF THE DAMMAM DOME, SAUDI ARABIA

M. NAMIK ÇAĞATAY

King Fahd University of Petroleum and Minerals, KFUPM Box 895
Dhahran 31261, Saudi Arabia

Abstract—Clay mineralogy and petrography of the Early to Middle Eocene succession of the Dammam dome, Saudi Arabia, comprising the Rus and Dammam Formations, were studied using X-ray powder diffraction, light microscopy, and scanning electron microscopy. These formations consist of alternations of dolomite, dolomitic marl, claystone, and shale. The rocks were deposited and subjected to early diagenetic dolomitization in a shallow, coastal marginal basin characterized by rapid changes in salinity. Palygorskite occurs as interwoven fibrous mats forming fine laminae in shales and as coatings and pore-filling and pore-bridging cements in dolomitic marls. This textural evidence suggests a direct chemical precipitation, mostly post-dating dolomitization. Magnesium concentrations in presence of dolomite was sufficient for palygorskite precipitation; the necessary Si and Al were derived by dissolution of silicates under alkaline conditions. The maximum development of palygorskite was near the top of the Dammam Formation, which was deposited during a marine transgression in the Lutetian. The formation of palygorskite in marginal restricted basins in eastern Saudi Arabia took place during Paleocene-Middle Eocene time and was contemporaneous with similar occurrences in the Tertiary basins of West Africa.

Key Words—Dedolimitization, Diagenesis, Palygorskite, Petrography, Saudi Arabia, Scanning electron microscopy, X-ray powder diffraction.

INTRODUCTION

The formation of palygorskite has been documented in marginal marine basins and lagoons under warm climatic conditions (Weaver and Beck, 1977; Weaver, 1984; Millot, 1970; Isphording, 1973, 1984). The occurrence of palygorskite in some Paleogene formations of Saudi Arabia and Bahrain have also been reported. Shadfan *et al.* (1985) identified palygorskite in the Paleocene Umm er Radhuma Formation in Khurais, about 250 km WSW of Dammam, Saudi Arabia, and in the Khobar Member of the Dammam Formation in the Dammam area. Doornkamp *et al.* (1980) reported the presence of this mineral in the stratigraphically equivalent formations in Bahrain, and Çağatay (1988) noted palygorskite in the Eocene Rus Formation and the Midra and Saila Shale Members of the Dammam Formation. These previous studies of palygorskite in the Tertiary rocks of eastern Arabia, however, were mostly descriptive and did not elaborate on the formation of the mineral.

The present paper examines the occurrence of palygorskite in the Eocene succession of the Dammam dome in the Eastern Province of Saudi Arabia (Figure 1). The aim of the study was to obtain an understanding of palygorskite genesis in these rocks, especially in relation to depositional environment and dolomitization of the rocks.

GEOLOGY

The Dammam dome, the structure that marked the first oil discovery in Saudi Arabia in 1936, is on the coast of the Arabian Gulf in eastern Saudi Arabia (Figure 1). The dome is a gentle structural rise above the flat topography of the Arabian coastal plain and comprises a number of hills having a maximum elevation of 140 m at Jabal Umm er Rus. Because of its oval shape, complex faulting, and strong negative gravity anomaly, the dome is believed to be due to a deep-seated salt intrusion (Powers *et al.*, 1966).

Within the dome structure a succession of rocks ranging in age from Paleocene to Middle Miocene crops out (Figures 1 and 2). The top of the Umm er Radhuma Formation (Paleocene-Early Eocene) is represented by a 3-m-thick yellowish dolomite (Tleel, 1973) in a single small outcrop, now covered by buildings. The overlying Rus Formation consists of chalky carbonates and marls in the upper part and geode-bearing dolomites in the lower part. The middle part of the Rus Formation contains anhydrite in the subsurface outside the Dammam dome (Powers *et al.*, 1966). The Midra and Saila Shale Members of the Dammam Formation consist essentially of grey to tan calcareous mudstones and shales and intercalated dolomite beds and conformably overlie the chalky carbonates of the Rus Formation. The mudrocks are followed by the light-colored dolomitic limestone of the Alveolina Member and limestones, dolomites, and marls of the Khobar Member. The presence of the Alat Member of the Dammam Formation in the Dammam dome has not been ascertained (Tleel, 1973; Al-Tamimi, 1985). The various carbonate facies of the Miocene Dam Formation overlie the older formations in the dome with an angular unconformity (Tleel, 1973).

Through structural growth after the Early Eocene, the Dammam dome became a positive topographic feature until the major Miocene transgression (Tleel, 1973). Similar Eocene successions have been observed in the Bahrain (Willis, 1967; Doornkamp *et al.*, 1980) and Qatar (Cavalier, 1975) structures, which also began to emerge and became positive structures during the Middle Eocene.

SAMPLING AND ANALYTICAL PROCEDURES

Forty-one representative fresh outcrop samples of the Rus and Dammam Formations were collected from three stratigraphic sections in the Dammam dome. The location and

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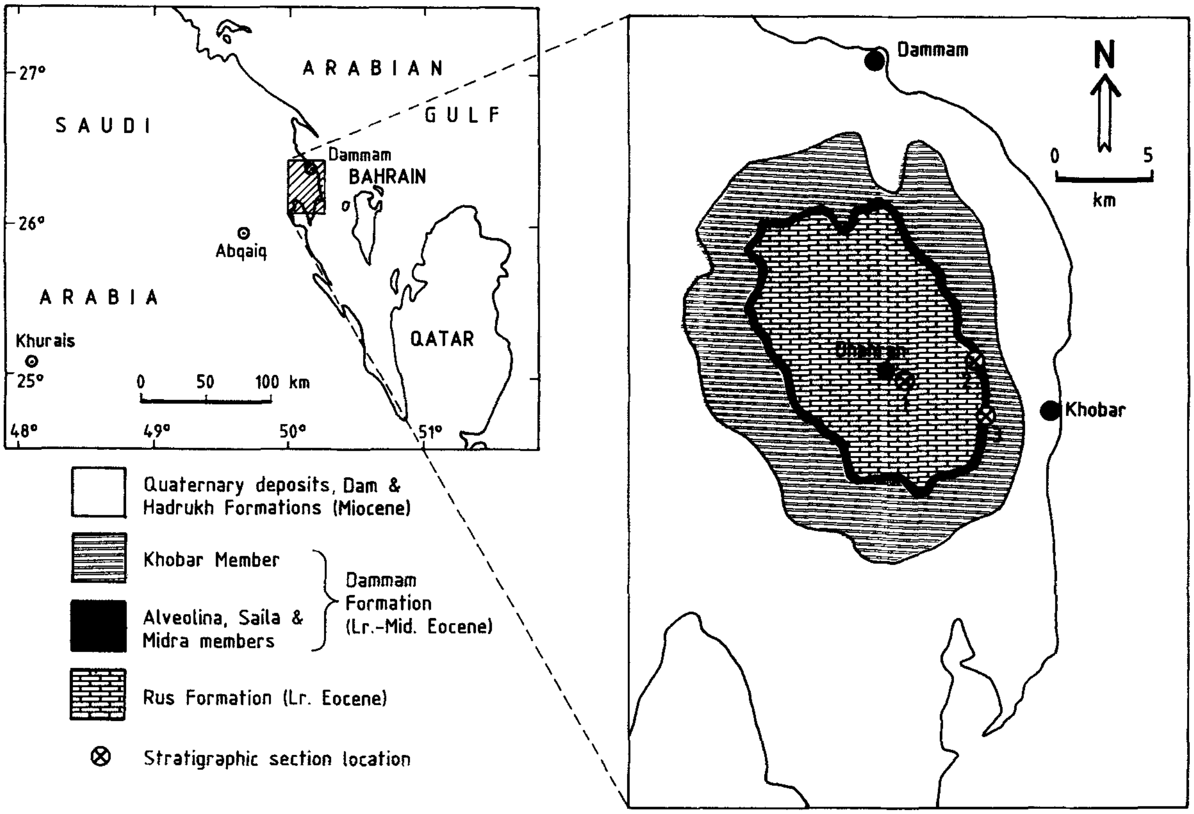

Figure 1. Maps showing the location and geology of the Dammam dome, Saudi Arabia (geology modified from Tleel, 1973).

stratigraphic position of the samples are shown in Figures 1 and 3, respectively.

Uncovered thin sections of the samples were prepared on large size (50 × 75 mm) glass slides for petrographic studies. The staining technique of Dickson (1965) was used for carbonate identification. Scanning electron microscope (SEM) studies were made on gold-coated sample chips using a JEOL JSM840 SEM equipped with an energy-dispersive X-ray analyzer.

For clay mineral analysis, the samples were mechanically disaggregated and ground by hand in a porcelain mortar. Ten grams of sample was dispersed in 500 ml of distilled water using a heavy-duty soil mixer. For marl and carbonate-rich samples, carbonates were decomposed in warm sodium acetate solution buffered at pH = 5 (Jackson, 1975). The <2-μm clay fractions of the samples were obtained by centrifuging the suspension at 500 cps for 12 min. The supernatant suspension was transferred to another centrifuge bottle and centrifuged at 3000 cps for 1 hr to sediment the clay fraction. The supernatant water was discarded, and the remaining clay fraction was suspended in 50 ml of water. A 2-ml aliquot of this suspension was pipeted onto a glass slide to obtain a preferentially oriented sample for X-ray powder diffraction (XRD) analysis.

XRD analysis was performed on a Philips diffractometer using Ni-filtered Cu radiation and a scan speed of $1°2\theta$/min. Cation saturation, organic solvation, and thermal treatment techniques were used to aid identification. Magnesium saturation was accomplished by suspending the clay fractions 1 M $MgCl_2$ solution and centrifuging the suspension. Ethylene glycol solvation of natural air-dried and cation-saturated samples were carried out by placing the sample in the solvent vapor for 24 hr. The pretreated samples were heated at 550°C for 2 hr after obtaining their diffractograms. Relative proportions of the clay minerals in the clay fractions were found using the "weighted" glycolated peak area method of Biscaye (1965). The peak area for the palygorskite and illite 10-Å reflections were measured collectively and then proportioned according to their peak heights at 10.5 and 10 Å, respectively. This clay analysis was at best semi-quantitative and gave trends of clay mineral distribution, rather than percentages. Part of each disaggregated sample was ground to <60 μm and placed on cavity mounts for XRD identification of the other minerals in the samples.

PETROGRAPHIC RESULTS

A 35-m-thick section of the lower dolomitic part is well exposed on the campus of the King Fahd University of Petroleum and Minerals near the center of the Dammam dome (section 1, Figure 3). Here, the rocks are light colored dolomites having an average grain size of 30 μm and containing quartz geodes. The rocks are vuggy and commonly contain coarse ($\leq$120 μm) dolomite grains, which locally show centripetal and centrifugal dedolomitization (i.e., replacement of dolomite by calcite). Some vugs are filled with gypsum or coarse blocky calcite. No fossils were observed by the author in the studied section.

Dolomite horizons in the upper part of the Rus For-

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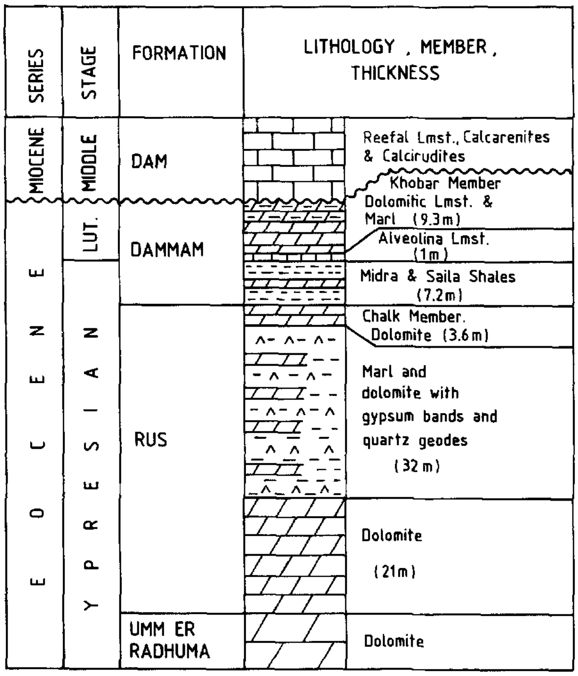

Figure 2. Generalized stratigraphy of rocks cropping out in the Dammam dome, Saudi Arabia.

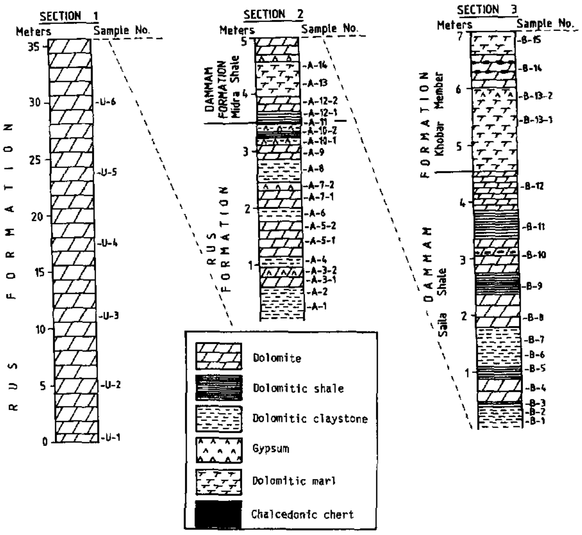

Figure 3. The studied sections of the Rus and Dammam Formations, Saudi Arabia.

mation (section 2, Figure 3) are chalky, white dolomites consisting of 4–10-μm-size dolomite crystals and having a microcavernous texture. The mudrock intercalations are dolomitic and generally nonfissile to subfissile. Both the dolomite and mudrock show mottled appearance; they have irregular crustacean burrows in several horizons and contain a rich assemblage of planktonic and benthonic foraminifers, together with pelecypods, echinoids, and ostracods (Al-Tamimi, 1985; and this study). These rocks also contain gypsum and quartz, the gypsum occurring as bands and veins in the upper part; the quartz is partially replaced by dolomite.

The boundary between the Rus and the overlying Dammam Formations is marked by a 5–10-cm-thick grey chert band (Al-Tamimi, 1985), consisting of globular bodies. Each glaebule is made up of alternations of narrow length-fast and wide length-slow chalcedonic quartz bands containing coarse crystalline quartz grain(s) in the center, which themselves contain 5–7-μm-size dolomite crystals (Figure 4).

The Midra and Saila Shales at the base of the Dammam Formation consists of pale yellow-orange to yellow-green shale and clay and very pale orange marl and dolomite. The shales are finely fissile (papyraceous) and contain clays, dolomite, and gypsum. The dolomitic marl is laminated and contains some pellet ghosts; it consists of dolomite and clay minerals and minor quartz, feldspar, and gypsum. The carbonate beds are 0.05–0.40 m in thickness and consist of equigranular dolomite crystals ranging from 3 to 8 μm in size from bed to bed. Locally the rocks contain fine-grained carbonate intraclasts of a few millimeters in diameter and vugs filled with fine-grained silica and locally gypsum. The Midra and Saila Shale Members contain dolomitized benthonic foraminifera, mollusks, and fish remains in some horizons. These rocks exhibit minor dedolomitization at some levels (e.g., sample A-12-2, Figure 3).

The Alveolina Member is generally about 1 m thick. It is a hard, microcrystalline, partly recrystallized and dolomitized limestone (Tleel, 1973); however, this unit was not positively recognized in section 3 (Figure 3). The Khobar Member of the Dammam Formation, as observed in section 3 (Figure 3), consists of white to pale-orange dolomitic marls and an intervening yellow-orange, thinly bedded dolomite. The marls are laminated and consist dominantly of clays and dolomite grains having an average diameter of 20 μm. Minor components are calcite, feldspar, and quartz. Quartz occurs as subhedral grains $\leq$80 μm in diameter and as cryptocystalline aggregates. The dolomite bed consists of euhedral to subhedral dolomite crystals having an average diameter of about 20 μm. The rock is dedolomitized to a minor degree and contains gypsum, quartz, and feldspar. Feldspar shows replacement by dolomite. The rocks of the Khobar Member are characterized by the occurrence of planktonic and benthonic foraminifers, fish remains, mollusks, echinoids, and ostracods.

CLAY MINERALOGY

Clay mineral assemblages of the studied sections of the Rus and Dammam Formations consist mainly of

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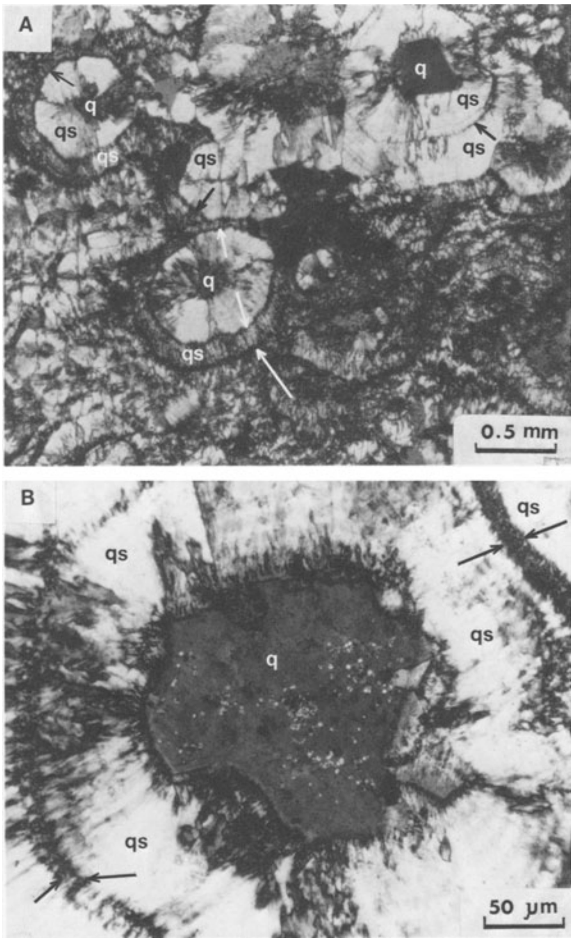

Figure 4. Thin section photomicrographs of chert in sample A-11 showing: (A) colloform glaebules containing wide length-slow (qs) and narrow length-fast (arrow) chalcedonic quartz, and central megaquartz (q); (B) silica glaebule having a central megaquartz containing dolomite crystals (crossed polars).

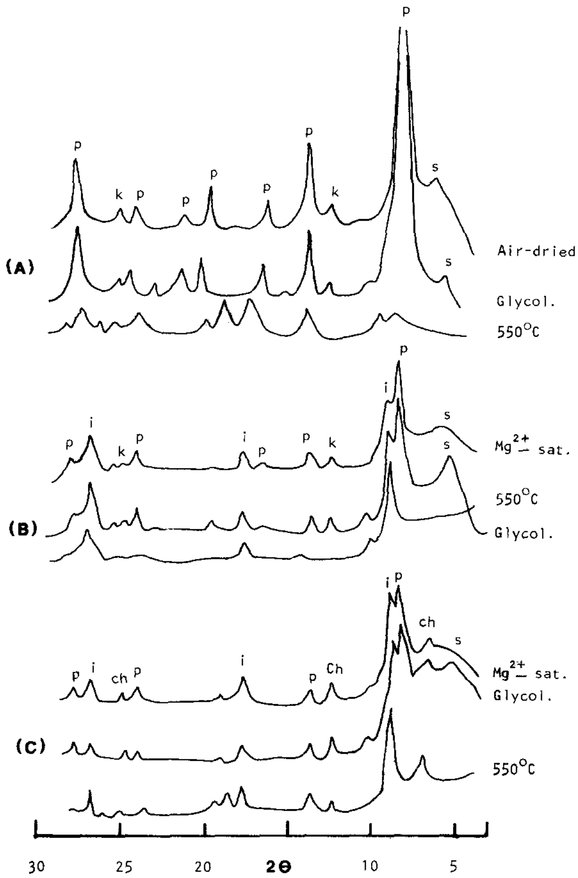

Figure 5. Representative diffractograms of oriented preparations of <2-μm fractions: (A) sample B-15, Khobar Member, Dammam Formation; (B) sample B-1, Saila Shale, Dammam Formation; (C) sample A-2, Rus Formation (p = palygorskite; i = illite; s = smectite; k = kaolinite; ch = chlorite). Ni-filtered Cu radiation.

palygorskite, illite, and smectite, with local occurrences of minor amounts of kaolinite and chlorite (Figure 5). No sepiolite was identified in these rocks. The relative percentage of the clay minerals in the clay fraction of the Eocene sequence is given in Figure 6. The lower dolomite part of the Rus Formation (section 1, Figure 3) did not yield sufficient clay minerals for XRD analysis and consequently is not represented in Figure 6. The presence of palygorskite in these rocks, however, was confirmed by SEM studies (Figure 7E).

Palygorskite is the most abundant clay mineral in the <2-μm fraction and commonly occurs as mats of interwoven fibers coating rhombs and glaebules of dolomite and grains of other minerals and lining and bridging cavities and pores (Figure 7). The mineral occurs as densely matted in the low-density, finely fissile shales (Figure 7A, 7B, and 7C) and loosely woven mats of coarser, longer fibers in the dolomitic marls (Figure 7D). Palygorskite also occurs as branch-like fibers about 0.3 μm wide and several tens of micrometers long (Figure 7F). Some fibers and mats are coated with halite and gypsum. The relative abundance of palygorskite in the <2-μm fraction of the Rus Formation ranges from 40 to 60% (Figure 6). The mineral averages about 60 and 40% in the clay fraction of the Midra and Saila Shales, respectively. In the Saila Shale, its relative abundance ranges from 25 to 65% and is lowest in the middle part. The relative and absolute abundance of palygorskite in the <2-μm fraction increases sharply in the marls in the Khobar Member (Figure 6).

Illite occurs as moderately to poorly crystalline forms (determined by XRD crystallinity measurements by Çağatay (1988, p. 58) in the Dammam rocks: see also Figure 5). Some illite is also present as spiny coatings on dolomite rhombs, growing into pore spaces (Figure 8). In the Rus Formation and Midra and Saila Shales,

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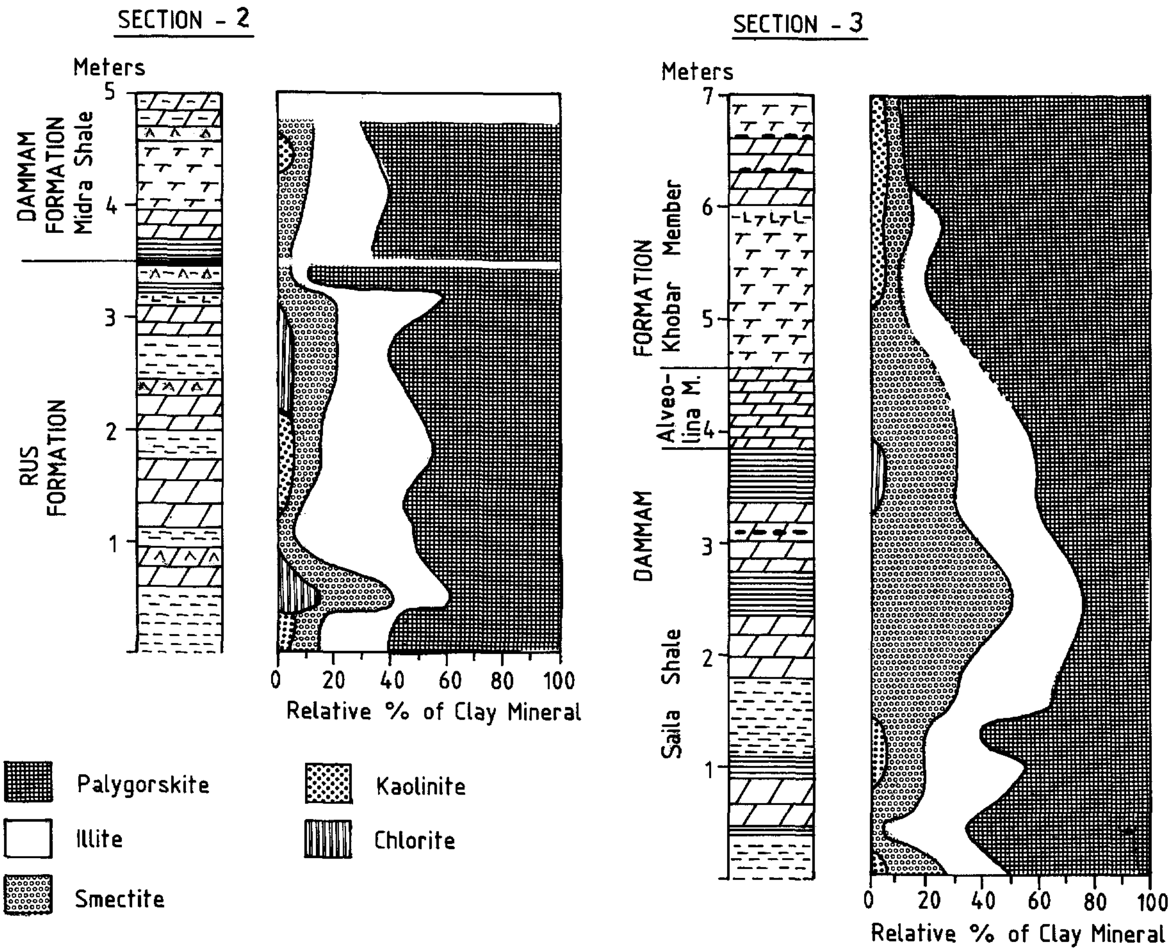

Figure 6. Distribution of the relative amount of clay minerals in the Rus and Dammam Formations. Carbonate-free material.

the abundance of the mineral in the <2-μm fraction ranges from 10 to 40%, but decreases sharply in the Khobar Member marls and dolomite and is undetectable near the top section 3 (Figure 6).

Smectite forms about 10% of the <2-μm fractions of the upper Rus Formation, the Midra Shale, and the Khobar Member (Figure 6). It increases in abundance to 50% in the clay fraction of the middle part of the Saila Shale.

Chlorite is of the 14-Å variety (see Velde, 1985; p. 174) and occurs in some levels of the Rus Formation and at the top of the Saila Shale (Figure 5C). Kaolinite occurs in several levels of the Rus and Dammam Formations as <2-μm-size anhedral to subhedral particles in these rocks.

DISCUSSION

Fossils within the Rus and Dammam Formations indicate that they were deposited under marine conditions. The presence of mottling due to crustacean burrows at several horizons and finely bedded and laminated dolostones in the studied sections of these formations indicates a shallow, oscillating sea level. Frequent emergence, especially during the deposition of the upper part of the Rus and the Midra and Saila Shale Members of the Dammam Formation was the result. The depositional surface was, however, deeper during the deposition of the Khobar rocks than the earlier Eocene rocks, as suggested by the abundance of foraminifer and mollusk fauna. Gypsum layers at several horizons throughout the succession suggest that the conditions were frequently hypersaline (evaporitic). These changes in depositional conditions probably reflect the growth of the Dammam dome during the deposition of the Rus and Dammam Formations. Similar conclusions were reached by Doornkamp *et al.* (1980) regarding the equivalent formations exposed in Bahrain, a structure 35 km east of the Dammam dome.

Dolomitization is persistent and uniform in the whole Eocene succession of the Dammam dome and is not confined to specific stratigraphic levels. The dolomite is fine grained (silt size) and commonly uniform in

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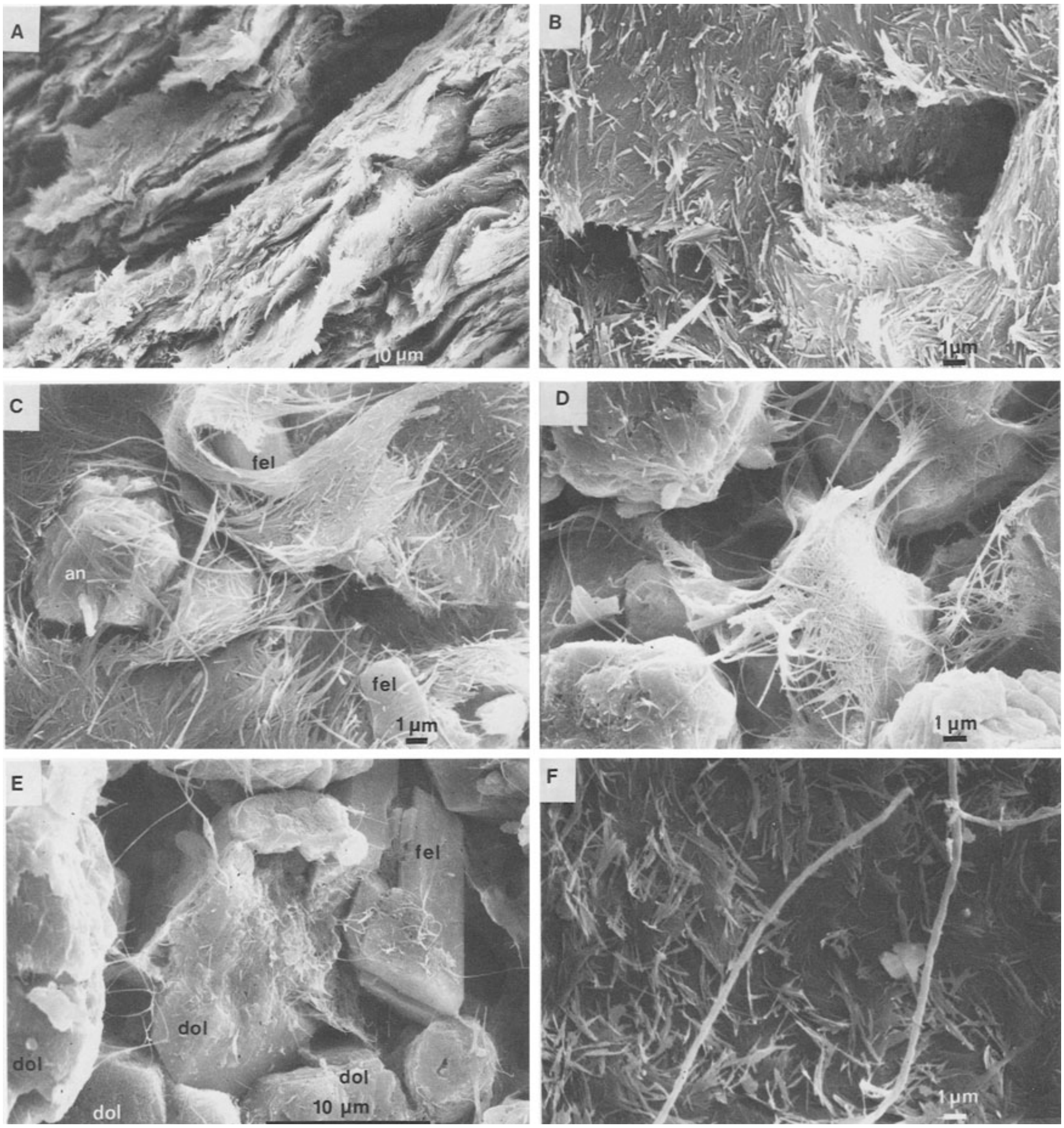

Figure 7. Scanning electron micrographs of (A) palygorskite forming mats of tightly interwoven fibers in finely fissile Midra Shale (sample A-12-1); (B) enlarged view of same sample, showing bundles of palygorskite (casts probably are of dolomite grains); (C) mats of interwoven fibers of palygorskite enveloping detrital (?) grains; TiO_2 mineral (probably anatase (an) and feldspar (fel) (top of the Rus Formation; sample A-10-2); (D) fibers and mats of palygorskite coating dolomite grains and bridging and lining pores between them (Midra Shale, sample A-13); (E) fibers of palygorskite coating dolomite (dol) grains and bridging pores between them (feldspar grain (fel) is also present (lower part of the Rus Formation, sample U-5)). (F) branch-like palygorskite with bundles and mats of shorter palygorskite fibers (Khobar Member, sample B-15).

grain size. The mineral constitutes >95% of the carbonate fraction; calcite occurs in minor amounts and was probably formed by dedolomitization. Except for the lower part of the Rus Formation, fossils are reasonably well preserved despite the pervasive dolomitization. All these features, according to Doornkamp *et al.* (1980), suggest a penecontemporaneous, early diagenetic dolomitization. Based on the oxygen and carbon isotope studies, Doornkamp *et al.* (1980, p. 61) further concluded that pervasive dolomitization and local dedolomitization of the Eocene succession of Bahrain occurred in a shallow basin by circulating ground waters.

The grain size of dolomite in the Eocene rocks of the Dammam dome changes sharply with stratigraphy. Dolomite is relatively coarse (30 μm) in the lower Rus;

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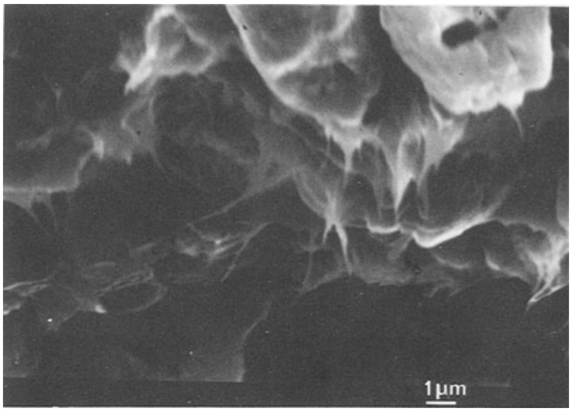

Figure 8. Scanning electron micrograph of spiny authigenic illite coating dolomite and projecting into pore spaces (Saila Shale, sample B-1).

fine (8 μm) in the upper Rus Formation and in the Saila and Midra shales, and intermediate (20 μm) in the Khobar marls and dolomites. Moreover, different episodes of dolomitization in these rocks probably took place, with replacement of fine dolomite by coarse dolomite being common (e.g., in samples U-3 and U-5 in section 1, A-9 and A-14 in section 2, and B-8 and B-12 in section 3). This, together with the local dedolomitization, suggests frequent variations in salinity of the environment; grain size of dolomite changes inversely with salinity (Folk and Siedlecka, 1974; Folk and Land, 1975).

Textural, sedimentological, and fossil evidence from the Eocene succession of the Dammam dome, therefore, point to a shallow, schizohaline, marginal basin for the deposition and dolomitization of these rocks. Such a depositional environment is characterized by high evaporation and periodic flushing with fresh waters, resulting in rapid fluctuations of salinity between hypersaline and nearly fresh water conditions (Folk and Siedlecka, 1974; Folk and Land, 1975; Longman, 1980). In schizohaline environments, mixing of marine and fresh waters can induce dolomitization at Mg/Ca ratios of as low as 1:1. The schizohaline model involving a shallow marginal basin is also in agreement with the geological history of the area. As discussed above, frequent oscillations of the sea level and emergence of the Dammam dome with the influx of ground water resulted in rapid changes in salinity. These frequent changes in salinity are also evident in the rapid alternations of length-fast and length-slow chalcedony in the chert horizon of the succession. Length-slow chalcedony has been attributed to rapid precipitation from highly saline, alkaline solutions (Folk and Pittman, 1971) whereas length-fast chalcedony and the central coarse-grained quartz indicate precipitation from relatively less saline and lower pH (high free CO_2) solutions (Folk and Pittman, 1971; Watts, 1980).

Textural evidence (SEM studies) shows that the palygorskite is authigenic and formed after than the dolomitization of the Eocene succession of the Dammam dome. Fine, delicate fibers and fibrous mats of palygorskite in these rocks preclude a detrital origin. Two possibilities for palygorskite genesis have been suggested: direct crystallization (e.g., Millot, 1970; Singer and Norrish, 1974; Isphording, 1984) and alteration of smectite (Yaalon and Wieder, 1976; Weaver and Beck, 1977; Weaver, 1984). The mode of formation of palygorskite by ion substitution of smectite has been considered unlikely because of significant differences in the structures of the two minerals (Singer, 1979). Moreover, Hassouba and Shaw (1980) described palygorskite without a smectite precursor in the caliche crusts of the Quarternary dune ridges in the coastal plain of northwest Egypt.

No textural evidence was found in the present study to suggest the formation of palygorskite by solid-solid transformation of smectite. The vague inverse relationship between the relative abundances of the two minerals in the Saila Shale (section 3, Figure 4) may be due to closed-number-system effect of relative percentages, rather than to alteration of smectite to palygorskite. The mode of origin, however, for some of the palygorskite in these rocks by a dissolution-precipitation process involving smectite is possible.

The SEM study shows palygorskite as fibrous mats and bundles forming fine laminae in the shales and as interwoven fibrous mats and fibers occurring as coatings and pore-filling and pore-bridging cement in the dolomitic marls. These textural features suggest direct chemical precipitation from Mg-rich solutions. The conditions necessary for palygorskite precipitation have been specified as high Mg and Si activity with some Al and a pH of about 8 (Weaver and Beck, 1977; El-prince *et al.*, 1979; Velde, 1985, p. 228). Singer (1984a, p. 173) pointed out that if palygorskite coexists with dolomite, the concentration of Mg in solution has been found to be adequate for palygorskite formation. Therefore, Mg concentrations of the mixed fresh-marine waters were sufficient to cause dolomitization and the subsequent precipitation of palygorskite. The source of Mg is believed to have been sea water. Chert is common in thin layers and solution cavity fillings in the Eocene rocks of the Dammam rock suggesting the availability of an ample supply of silica for the formation of palygorskite. The silica, probably derived by the weathering of silicates during short, relatively humid periods, migrated in surface and ground waters to the basin of deposition. Some silica and alumina may have also been released from detrital quartz and silicates under high pH conditions.

The widespread occurrence of palygorskite in the studied Eocene succession suggests that the formation of palygorskite was not dependent on salinity and that it formed continuously at variable rates. The presence

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in some samples of gypsum locally coated by palygorskite, for example, suggests that palygorskite also precipitated from hypersaline solutions during dry intervals. The rise in the relative and absolute abundances of palygorskite in the Khobar marls and dolomites is probably due to a rise of sea level (i.e., local transgression). This may have given rise to less detritus and more chemical sedimentation in a relatively deeper basin, thus conforming with the seaward smectite-palygorskite-sepiolite succession of Millot (1970). The absence of sepiolite in the Dammam rocks is due to high Al/Mg ratios (suggested by the presence of smectite) in the presence of excess silica (Velde, 1985, p. 253).

That neither chlorite nor kaolinite can coexist with palygorskite in the presence of a silica phase (Velde, 1985, p. 241) suggests that both the chlorite and kaolinite in the Eocene rocks of the Dammam dome are probably detrital. No conclusive textural evidence exists for the origin of smectite; it could be of detrital and/or chemical origin (Velde, 1985, p. 231; Millot, 1970, p. 272). The poor (degraded) crystallinity of illite, suggests a detrital origin. Textural evidence, however, indicates that some authigenic illite is also present (Figure 8).

Occurrences of palygorskite in various restricted and semi-restricted basins have been documented by previous workers (Millot, 1970; Weaver and Beck, 1977; Isphording, 1973, 1984; Chamley, 1979). These studies stressed the importance of basin morphology and, to a lesser extent, climate for the formation of this mineral. The presence of palygorskite, along with smectite and chlorite, suggest a hot (arid to semiarid) climate with some rainy intervals (Chamley, 1979; see also review by Singer, 1984b). The occurrence of detrital chlorite and illite suggests a reduced intensity of chemical weathering under dry or cold climates (Chamley *et al.*, 1977a, 1977b). Thus, during the deposition of the Eocene succession in eastern Saudi Arabia the climate was probably arid to semiarid with some humid intervals. The alternating presence of minor amounts of chlorite and kaolinite in the succession was probably due to the dry and more humid intervals, respectively.

During Paleocene-Middle Eocene time, eastern Saudi Arabia was covered with a wide, shallow, evaporitic platform, which was separated from the open-marine basin to the northeast by a shallow carbonate platform over the Qatar-South Fars arc (Murris, 1980). This large, shallow, marginal basin was divided into small, semi-restricted basins by structural highs, such as the Ghawar anticline, the Dammam dome, and the Bahrain structure (Figure 9). Palygorskite began to precipitate in these schizohaline peripheral basins over the Arabian Peninsula and Bahrain during the Paleocene (Shadfan *et al.*, 1985; Doornkamp *et al.*, 1980) and continued during the Ypresian; it reached a maximum during Lutetian time. The palygorskite-bearing Eocene succession of the Dammam dome was, therefore, contemporaneous with similar successions in the Tertiary basins of west Africa, described by Millot (1970, pp. 262–272).

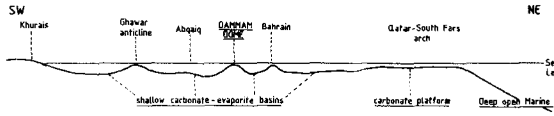

Figure 9. Paleocene to Middle Eocene environments of deposition over eastern Saudi Arabia and Arabian Gulf.

SUMMARY AND CONCLUSIONS

Palygorskite in the Early to Middle Eocene succession of the Dammam dome formed mainly in a coastal, schizohaline environment, under an arid to semiarid climate with humid intervals. It formed shortly after the deposition and contemporaneous dolomitization of the rocks and reached a maximum during a transgression in which the Khobar marls and carbonates were depositied during the Lutetian. Mg concentrations, in presence of dolomite was adequate for the palygorskite precipitation, with Si and Al supplied by the dissolution of silicates under alkaline conditions. The development of palygorskite in the schizohaline marginal basins in eastern Arabia during the Paleocene-Middle Eocene interval is contemporaneous with similar occurrences in the Tertiary basins of West Africa.

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