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Origin of ferricretes in fluvial-marine deposits of the Lower Cenomanian Bahariya Formation, Bahariya Oasis, Western Desert, Egypt

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ABSTRACT

The type section of the Lower Cenomanian Bahariya Formation at Gebel El-Dist (Bahariya Oasis, Western Desert), Egypt, comprises claystones, mudstones, siltstones and sandstones deposited in fluvial-deltaic coastal plain, lagoonal, estuarine and shallow marine environments. The formation is characterized by an abundance of ferruginous sandstones that locally weather to form prominent iron crusts. These centimeter to decimeter-scale ferruginous horizons display a continuum of features ranging from unaltered sandstone with a pervasive ferruginous matrix to distinct ironstone beds with massive, nodular, vesicular and pisolitic textures. Ferruginous sandstone typically occurs at the tops of sandstone beds, or bracketing the base and top of beds, in the fining-upward cycles of deltaic plain deposits in the lower part of the formation and on a low-energy fluvial floodplain in the middle of the formation. Indurated ironstone beds occur mainly as the caps of coarsening-upward cycles of prograding shoreface sediments through much of the formation. We interpret the ironstone crusts as ferricretes, formed by iron accumulation that resulted from the oxidation and precipitation of soluble iron or colloids transported in the sediment load or by groundwater. This accumulation possibly took place at the water table or possibly below the water table at the fresh water/saline water interface. However, base-level fall and subsequent subaerial exposure of the sediments resulted in reworking and pedogenic modification of some of the iron-impregnated horizons.

1. Introduction

The term ferricrete is a widely used, but poorly constrained term that identifies an iron-cemented crust formed by various processes in sedimentary strata, particularly pedogenesis. The terms ferricrete and laterite have been used almost interchangeably. McFarlane (1976) clearly intended that laterite refer specifically to a tropical residual soil, but noted that iron crusts (variously termed "sheet crusts" or "gallery crusts") may form below the base of the soil-forming environment as a result of groundwater action, not pedogenesis. Goldbery and Beyth (1984), however, described the iron concretionary zones that overlie unaltered sandstones at Wadi Budra in the Sinai as "laterite profiles," although they acknowledged that a landscape reduction model of laterite formation, as presented by McFarlane (1976), was not consistent with these features. These authors (Goldbery and Beyth, 1984) speculated that it appeared more likely that soluble Fe^{2+} in reduced groundwater from an organic-rich source migrated into channel and overbank sediments, and that precipitation was controlled by seasonal fluctuations in the water table.

Tardy (1992) presented a broad definition for the term laterite, although he clearly intended that it refer to the products of weathering. Further, he used the term ferricrete to describe a type of laterite with an iron crust and characterized by a specific weathering profile. Bourman (1993), acknowledging that the breadth of coverage by the term laterite is a problem, used the term ferricrete in a strictly lithologic but nongenetic sense, as did Ollier and Pain (1996). Suprapan et al. (2001) continued this broader usage when they described the formation of "pedogenic ferricretes" in the subsoils of oxisols/ferralsols on a tropical coastal lowland plain in Indonesia. Achyuthan (2004) furthered the broader sense of ferricrete in using the term to designate an indurated crust within a weathering profile. Conversely, Phillips (2000), following Goudie (1985) and Pain and Ollier (1992), restricted the term ferricrete to refer to regolith in an indurated state due to cementation by iron in the zone of water table fluctuation, thus distinguishing ferricrete from laterite, as earlier defined by McFarlane (1983), Ollier (1991), Aleva (1994) and Widdowson (2007). Widdowson (2007), for example, described ferricrete as an "alteration profile," formed by the accumulation of allochthonous iron. Pickett (2003) commented usefully on the importance of recognizing features of pedogenic profiles to distinguish laterites from ferricretes. This paper follows the usage of Widdowson (2007) and earlier workers in considering

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ferricretes as iron-cemented regolith formed primarily through non-pedogenic processes. The broader term ironstone is used in reference to all iron-enriched sedimentary strata, regardless of the mode of enrichment.

In this study, we describe the ferricretes and ferruginous sandstones in strata of the Lower Cenomanian (Upper Cretaceous) Bahariya Formation of the Western Desert of Egypt and discuss their genesis and depositional context.

2. Geologic setting

The Bahariya Oasis, located in the Western Desert between latitudes 27°48′ and 28°30′N and longitudes 28°32′ and 29°10′E (Fig. 1) is one of the best known areas in the Western Desert, having been studied intensely over the last four decades following the discovery of economically significant iron ore deposits in the region (El Akkad and Issawi, 1963; Issawi, 1972; Franks, 1982; Dominik, 1985; Soliman and Khalifa, 1993; Khalifa et al., 2002, 2003). The best known and most studied ironstones of the Bahariya depression are the deposits of the Ghorabi mine area (Fig. 1). This unconformity bounded Eocene succession hosts ironstones within facies interpreted as lagoonal mudstones and shallow marine nummulitic-bioclastic wackestones/packstones (El Aref et al., 2006a,b).

The Bahariya Formation, of Early Cenomanian age, is particularly well-known for a rich fauna that includes decapod crustaceans, chondrichthyans, osteichthyans, turtles, plesiosaurs, crocydiloforms, and large dinosaurs (see reviews in Smith et al., 2001; Schweitzer et al., 2003). Most of this fauna is known from a single locality, the hillside known as Gebel El-Dist in the northern part of the Bahariya Oasis. This is the type location for the formation and the site of this study (Fig. 1).

During the Late Cretaceous, the Bahariya Oasis was located on a passive continental margin formed by opening and widening of the Tethys Sea beginning in the Jurassic (El Emam et al., 1990). By Early Cenomanian time, sedimentation on the continental shelf was likely controlled by an overall gradual base-level rise, during which an extensive succession of paralic deposits was deposited (Ibrahim, 1990; Said, 1990). Catuneanu et al. (2006) interpreted the more or less constant thickness of the Bahariya Formation across the region as suggesting that formation of accommodation space during this time was limited to between 100 and 200 m, although they noted that the thickness of the Bahariya Formation increases up to 400–500 m in localized fault-bounded basins to the north of the Oasis on an unstable shelf structural province. Said (1962) introduced the name Bahariya Formation for the Cenomanian sandstones and claystones that outcrop on the floor and along the escarpments of the depression that had earlier been designated the Bahari-Jestufe by Stromer (1914). Said (1962) described the formation as consisting mostly of sandstones with numerous interbedded ferruginous layers. The age of the Bahariya Formation is now well established as Early Cenomanian (e.g., Soliman and Khalifa, 1993).

3. Methods

Ferruginous facies of the Bahariya Formation were described and sampled at Gebel El-Dist. Field description included logging of the dry-rock colors using the Munsell color system of hue, value and chroma. Standard petrographic thin sections were prepared and examined for analysis of microfabrics. These microfabrics were also examined by scanning electron microscopy of gold-coated specimens on a JEOL JSM-5200 JVM scanning electron microscope operating at an accelerating voltage of 20 kV at Shinshu University, Japan. Additional scanning electron microscopy was performed on gold-coated specimens with an Amray 100D SEM operating at 20 kV at Le Moyne College, New York. The mineralogy of the ferruginous facies was determined by X-ray diffraction of bulk powder specimens with a Philips PW3040 diffractometer operating at 40 kV using Cu Kα radiation, also at Shinshu University.

4. Lithostratigraphy of the Bahariya Formation

This study focuses on the type section at Gebel El-Dist. El Bassyouny (2004) reported that in the subsurface in the El-Harra region, the base of the Bahariya Formation lies unconformably over crystalline basement. The base of the Bahariya Formation is not

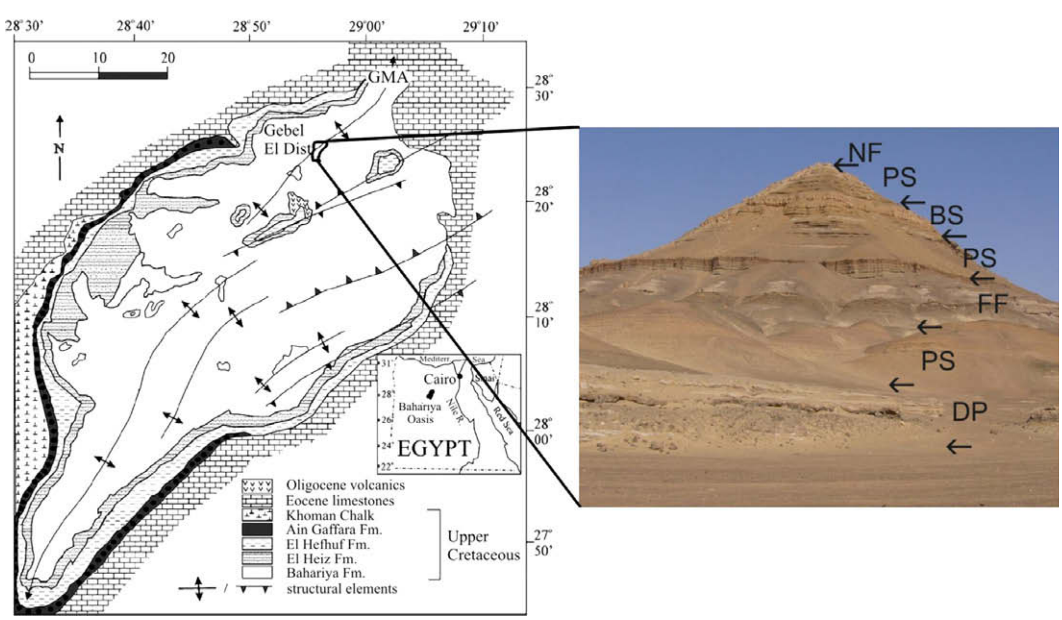

Fig. 1. Location of the study area: generalized geologic map of the Bahariya Oasis illustrates location of Gebel El-Dist, the type locality for the Bahariya Formation and the Ghorabi mine area (GMA) (after Catuneanu et al., 2006). Inset shows Gebel El-Dist. The base of the formation is not exposed here. Facies associations, as described by Catuneanu et al. (2006): DP, deltaic plain; PS, prograding shoreface; FF, fluvial floodplain; BS, braided stream. The limestone cap at the very top of the hill is the Naqb Formation (NF). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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exposed in the Bahariya Oasis and is presumed to overly crystalline basement here as well (Catuneanu et al., 2006). At its upper contact at Gebel El-Dist and at the northern escarpment of the Oasis, the Bahariya Formation is unconformably overlain by the Middle Eocene Naqb Formation, while at the eastern and western escarpments around the Oasis the formation is unconformably overlain by the Upper Cenomanian El-Heiz Formation (Khalifa and Abu El-Hassan, 1993). The thickness of the Bahariya Formation exposures in the Oasis varies from about 90 m to over 100 m (Catuneanu et al., 2006).

The Bahariya Formation at Gebel El-Dist consists of approximately 110 m of sedimentary strata, comprising claystone, mudstone, siltstone and sandstone, with minor beds and lenses of gypsum pervasive throughout the section. Previous workers have interpreted the interbedded mudstones and cross-bedded to flaser-bedded sandstones that characterize much of the lower part of the formation at the type locality as sediments deposited in a paralic environment along a low-energy coastline. Deposition occurred under the influence of tides, likely as lagoonal and vegetated tidal flat to tidal-channel deposits (Lacovara et al., 2000; Smith et al., 2001; Schweitzer et al., 2003; Mesaed, 2006). More comprehensive studies of the sedimentology and sequence stratigraphy of the Bahariya Formation were provided by Catuneanu et al. (2006) and Khalifa and Catuneanu (2008). These authors have interpreted the Bahariya Formation at Gebel El-Dist as mainly the deposition of back-stepping aggradational facies during an overall transgressive episode, but punctuated episodically by episodes of landscape incision during intervals of lower base-level (Khalifa and Catuneanu, 2008).

Catuneanu et al. (2006) described four main facies associations present at Gebel El-Dist (Fig. 1), three of which contain ironstone crusts or ferruginous sandstone beds (see Fig. 3 in Catuneanu et al., 2006). The basal strata comprise fining-upward sandstone–mudstone cycles deposited as a deltaic plain association. These are overlain by coarsening-upward cycles of mudstone–siltstone–sandstone, deposited in prograding shoreface packages. The succeeding strata, consisting of alternating claystones and sandstones, represent the deposits of a fluvial floodplain association. These are overlain by another section of coarsening-upward shoreface cycles, which are in turn succeeded by channelized sandstones that may have been the deposits of a braided stream facies association. The uppermost strata at Gebel El-Dist record a return to cyclical prograding shoreface deposition. The ferruginous facies that are the focus of this paper occur in all of these facies with the exception of the channelized sandstones. The reader is referred to Catuneanu et al. (2006) and to Khalifa and Catuneanu (2008) for detailed interpretations of the sequence stratigraphy and sedimentology of the Bahariya Formation. In the following section we offer sedimentological observations beyond those previously published in order to provide context for discussion of the occurrence and genesis of the ironstones.

5. Field description of the ferruginous facies

Ferruginous facies within the section include both ferruginous sandstones and ironstone crusts. The former are beds of sandstone with a pervasive iron stain in which primary sedimentary structures are visible, whereas the latter are exceedingly well-indurated iron-cemented beds that stand out prominently on differential weathering. These beds may be simple, discrete units a few centimeters thick, or complex units decimeters thick that occur as amalgamations of several thinner units, locally separated by thin (several centimeters or less) lenses or layers of siltstone or ferruginous sandstone. The lower and upper contacts of the beds are commonly sharp and irregular, and the texture of the beds varies from massive to brecciated, nodular, or pisolitic. Previous authors (Catuneanu et al., 2006; Mesaed, 2006; Khalifa and Catuneanu, 2008) have interpreted these ironstone crusts as ferricretes formed by lateritic weathering on subaerial exposure of glauconitic facies within the cyclothems.

5.1. Deltaic plain

The basal 15 m of strata at Gebel El-Dist consist of meter-scale fining-upward sandstone–mudstone cycles that were interpreted by Catuneanu et al. (2006) as sediments deposited on a deltaic plain formed as a lowstand systems tract (see Fig. 3 of Catuneanu et al., 2006). The mudstones are dark grey to dark brown and contain abundant plant remains, siderite nodules and are locally fossiliferous. The sandstones are lenticular, well-burrowed and massive to planar cross-bedded, locally heterolithic, and in places form ball and pillow structures at the contact with underlying mudstones (Fig. 2A and B). Iron accumulation in these strata occurs in discontinuous patches, centimeters to several decimeters in width, to bands that are continuous across the outcrop face (Fig. 2A and C). The iron occurs as light to dark yellowish-orange to orange-brown (10YR 8/6 to 10YR 5/6) stain in sandstone beds that are 2–10 cm in thickness (Fig. 2A). This stain pervades thinner sandstone beds, but more typically is concentrated at the contacts with the enclosing lithology, either at the bases of sandstone beds or at both the base and top. Locally, the iron-cemented sandstones weather to form discontinuous crusts (Fig. 2C and D). These ferruginous sandstones are most prominent where the interbedded mudstones are dark brown and enriched in organic matter and iron, rather than grey.

5.2. Prograding shoreface

Overlying the deltaic plain facies association are strata consisting of centimeter to decimeter-scale layers of alternating grey siltstone/mudstone and brown sandstone/grey siltstone, with minor interbedded gypsum, arranged in coarsening-upward packages that average one meter in thickness and thin upwards. The sandstones typically are glauconitic, well-bioturbated and either lack primary sedimentary structures or display relict ripple lamination (Fig. 3A and B). Catuneanu et al. (2006) considered these strata as cycles of prograding (shallowing-upward) shoreface sediments, deposited as back-stepping parasequences within transgressive systems tracts. This facies association comprises a substantial portion of the section at Gebel El-Dist, approximately 60 m, as it occurs at three stratigraphic levels within the section (see Catuneanu et al., 2006). Most of the ironstone crusts in the section at Gebel El-Dist occur in this facies association.

The sandstones within the coarsening-upward cycles in the lower interval (15–29 m in Fig. 3 of Catuneanu et al., 2006) typically display pervasive iron staining that is most concentrated at the boundaries with the interbedded silt/mudstones and increases upwards within the individual coarsening-thinning-upward cycles. The cycles are capped by 5–15 cm-thick ironstone crusts (Fig. 3A and B). These crusts are semi-indurated to well-indurated, dark red to reddish-brown to yellow-orange (5R 2/6 to 10R 3/4 to 10YR 6/6), and characteristically weather to form beds with an irregular to somewhat nodular appearing surface (Fig. 3C and D). Upon fresh exposure, the crusts exhibit massive to brecciated fabrics. The crusts display abrupt irregular contacts to gradational contacts with underlying beds, and are overlain abruptly by the succeeding beds. In some instances, reddish iron staining is diffused into the underlying bed even where the lithologic contact between the beds is distinct (Fig. 3D). The crusts commonly contain iron-cemented root casts and lags of bivalves (*Ostrea* and *Exogyra*) in which the shell has been replaced by iron (Fig. 3E). As noted, there is a thinning-upward trend for the thickness of

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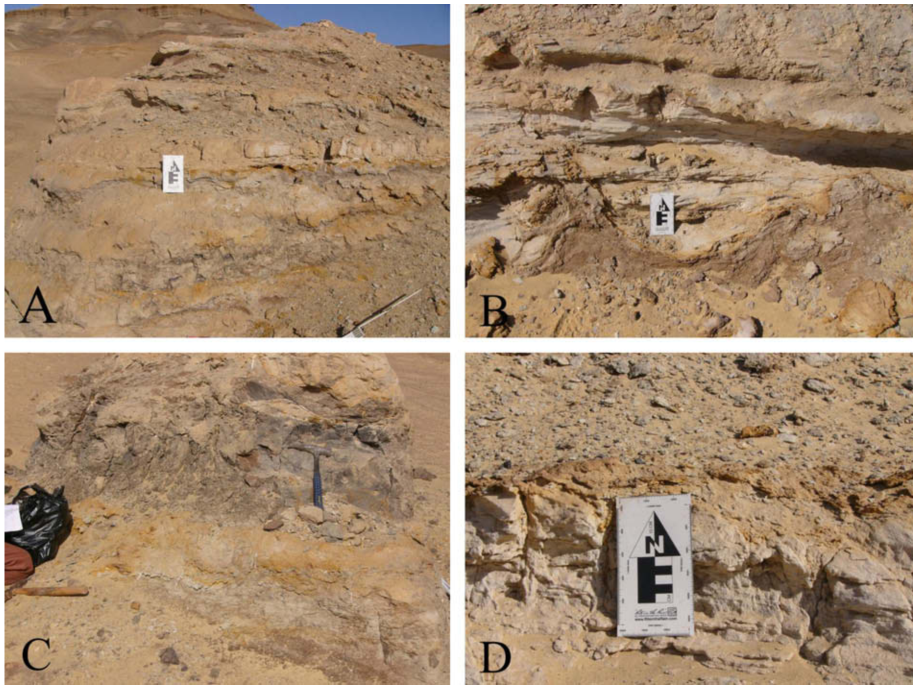

Fig. 2. Features of ferruginous sandstones and ironstone crusts in the deltaic plain facies association. (A) Heterolithic channel fill near the base of the section, with ferruginous banding locally at the sandstone/mudstone contacts. Arrow in scale card is 10 cm. (B) Soft-sediment deformation (ball and pillow) structure with sandstone pillow surrounded by mudstone. Ferruginous cementation of the sandstone is confined to the sandstone contacts. (C) Two ferruginous sandstones separated by an interval of brown, organic-rich mudstone. The lower sandstone (below the hammer handle) is pervasively cemented and weathers to form a discontinuous crust. (D) Ferricrete crust caps a well-sorted quartzose sandstone. The ferricrete is overlain by dark brown, organic-rich mudstone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the cycles. Consequently, the ironstone crusts in the upper parts of the prograding shoreface intervals are spaced only decimeters apart (Fig. 3F).

The second interval of prograding shoreface cycles (49–65 m in Fig. 3 of Catuneanu et al., 2006) overlies the fluvial floodplain facies association described below. The ironstone crusts in this interval differ in color, dusky brown (5YR 3/4 to 5 YR 2/2), from those in the lower prograding shoreface interval. The siltstone here may be burrowed and contain desiccation cracks and commonly is penetrated by vertical, downward tapering, iron-cemented root casts that are up to 40 cm long (Fig. 4A). The second coarsening-upward cycle in this interval is distinctive in that it comprises one meter of grey siltstone containing siderite nodules, overlain by 60 cm of ironstone comprising three distinct crust layers (Fig. 4B). The individual ironstone crusts are separated by thin (5–10 cm) ferruginous sandstones and contain cm-scale root tubules, voids and concretions (4C). As in the interval of prograding shoreface described above, the crusts are typically fossiliferous, but also may contain scattered cm-scale pisoliths that display a crude concentric internal layering (Fig. 4D). Numerous meter-scale coarsening-upward cycles within this interval lack well-developed iron crusts, but instead display desiccation cracks and dark yellow-orange (10YR 6/6) ferruginous sandstone. The intervening mudstones are grey and rich in plant remains and contain discontinuous bands and isolated nodules of siderite. The uppermost portion of this interval is a 3-m-thick coarsening-upward sequence of interbedded grey claystone, reddish mudstone with sandstone lenticles and ironstone nodules, and ferruginous sandstone, all in parallel layers. (Fig. 4E), likely recording deposition of progradational facies in a tidally influenced lagoonal or estuarine environment. Also within the uppermost 3 m are sandstone-hosted ironstone crusts with irregular bases, suggestive of soft-sediment (load) deformation. The thickness of these beds increases upward within the interval (Fig. 4E).

The uppermost 30 m of the section (78–110 m in Fig. 3 of Catuneanu et al., 2006) also consists of the prograding shoreface facies association, but here the facies comprise 2–4-m-thick coarsening-upward cycles of 30–40-cm-thick beds of grey laminated mudstone and cross-bedded fine-grained glauconitic sandstone (see analytical results below). The ironstone crusts in these cycles are generally nodular and fossiliferous, as in the lowermost interval of this facies association. The cycles continue upward repeatedly to the (unconformable) contact with the overlying Eocene El Naqb Formation (Fig. 4F).

5.3. Fluvial floodplain and channel facies

Between the lower and middle occurrences of the prograding shoreface cycles are 20 m of strata (29–49 m in Fig. 3 of Catuneanu et al., 2006) dominated by decimeter-scale beds of generally light- to dark-colored claystone capped by rooted, ferruginous sandstone beds and sandstone-hosted iron crusts up to 5 cm thick (Fig. 5A). This facies association was interpreted by Catuneanu et al. (2006) as the product of cyclical deposition by high-sinuosity streams and splays on a low-energy fluvial floodplain. The sandstones have red to brownish-orange iron-cemented boundaries at the contacts with the interbedded shales, which are typically laminated and organic rich. Sandstone lacking the iron cement is grey. The distinct ironstone crusts that characterize the prograding shoreface association are not present in this facies association.

Below the uppermost prograding shoreface interval are 13 m of strata dominated by meter-scale fining-upward beds of cross-bedded sandstone that are not ferruginous. The lowermost bed rests on the underlying strata with 1 m of erosional relief, locally truncating the uppermost ironstone crust capping the prograding shoreface cycle below (Fig. 5B). These sandstones were interpreted by Catuneanu et al. (2006) as the deposits of high-energy braided streams within a lowstand systems tract, although an alternative

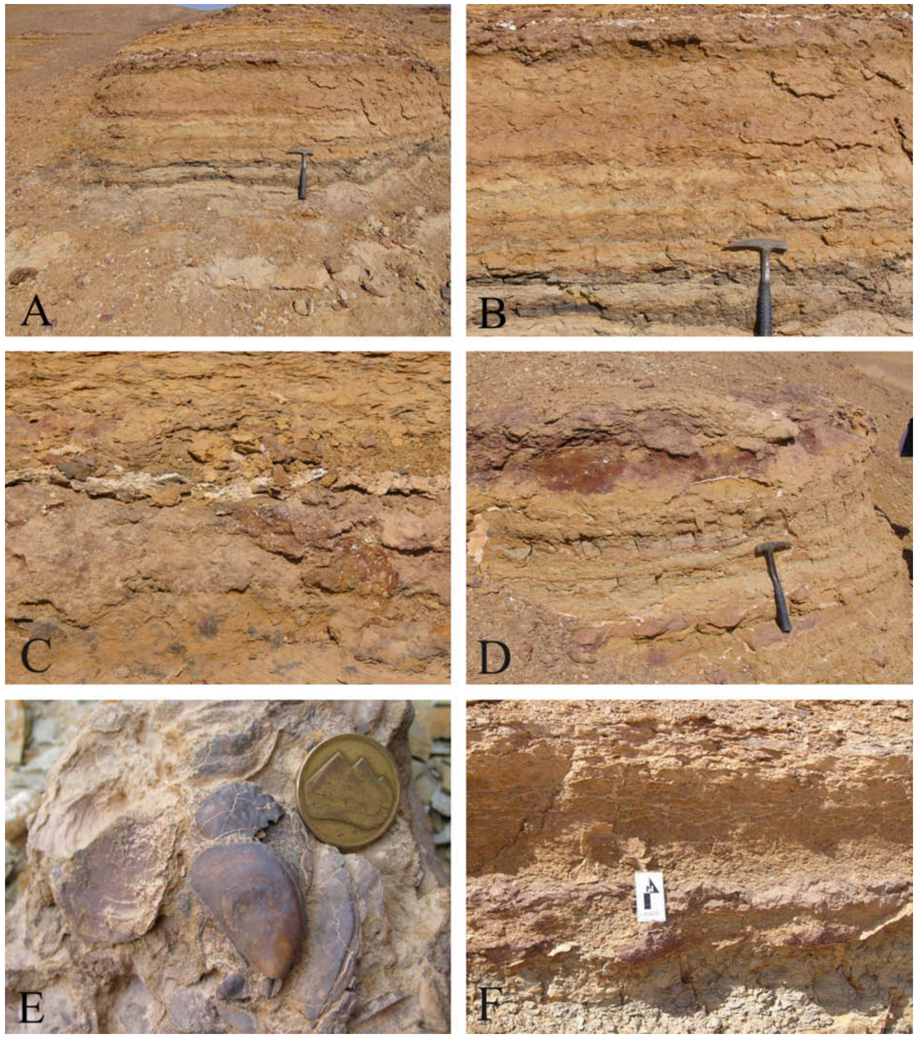

Fig. 3. Features of ferruginous sandstones and ironstones crusts in the lowermost interval of the prograding shoreface facies association. (A) Coarsening-upward mudstone–sandstone cycle in lowest occurrence of shoreface facies association. The handle of the hammer (28 cm long) rests on a sandstone-hosted ferricrete at the top of one cycle. The top of the succeeding cycle is a ferricrete 30 cm above the hammer head. (B) Detail of (A) illustrates the thinning, coarsening-upward nature of the cycle. From base to top of the cycle, mudstone beds become thinner, then disappear altogether in the upper 40 cm, which consists of bioturbated ferruginous sandstone capped by a ferricrete crust. (C) This 10-cm thick ferricrete, at the top of the cycle in (B), has weathered to a crudely nodular fabric. (D) The iron stain from this ironstone crust is diffused in the underlying fine-grained sandstone bed. (E) Lag deposit of shells of *Ostrea* that have been partially replaced by hematite in a ferricrete that caps a coarsening-upward cycle. (F) Two closely spaced coarsening-upward cycles capped by ironstone crusts. The base of the scale card rests on a discontinuous iron crust that is separated from the overlying crust (behind the scale card) by a thin mudstone.

interpretation, consistent with the depositional setting, would be that the sandstones represent the fill of tidal channels that incised the surrounding marsh deposits.

6. Analytical results

The ferruginous sandstones and ironstone crusts at Gebel El-Dist were studied by bulk powder X-ray diffraction, scanning electron microscopy and examination of petrographic thin sections. These analyses indicate that the different types of ironstones in the section are very similar in composition and differ mainly in the proportions of the components.

6.1. Mineralogy

Analysis by bulk powder X-ray diffraction demonstrates that the iron in both the ferruginous sandstones and the iron crusts is oxidized, including both goethite and hematite; goethite appears more consistently and prominently among the diffraction patterns generated for samples from various horizons in the Bahariya Formation, although hematite also appears in most samples, but less prominently (Fig. 6). Quartz is present in all of the samples, although the ferruginous sandstones and some iron crusts also contain detectable concentrations of chamosite. The clay mineral assemblage of the mudstones is dominated by kaolinite, with a minor contribution of illite. Siderite was detected in one sample of pisolitic ironstone.

Scanning electron microscopy demonstrates that the iron phase in most samples is a pore-filling material that varies from amorphous to consisting of microcrystalline rounded laths that are one to several micrometers in length (Fig. 7A). This latter morphology is consistent with the X-ray diffraction data described above for the predominance of goethite. Well-formed crystals of hematite were observed only rarely (Fig. 7B). Locally, the iron-oxide has a botryoidal to mammilary morphology (Fig. 7C and D) that may indicate a microbially mediated formation process (discussed below).

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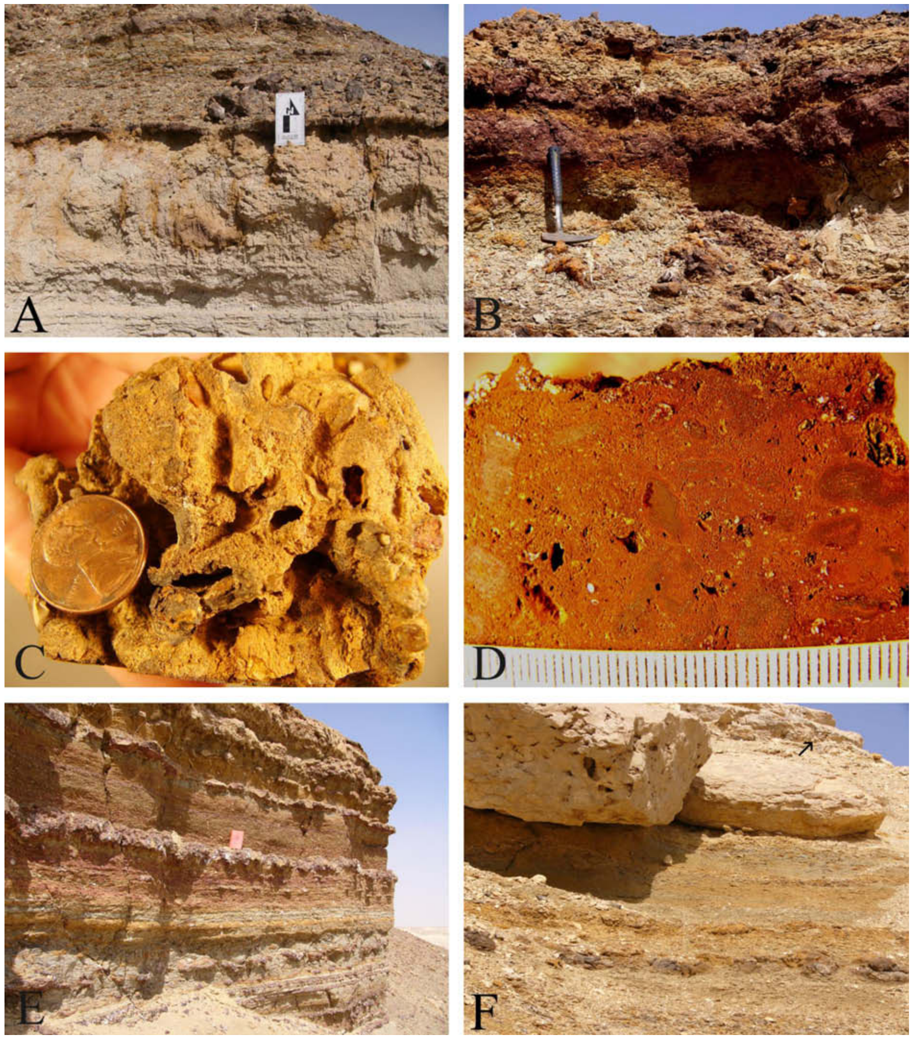

Fig. 4. Features of the ironstones in the middle interval of prograding shoreface facies association. (A) Iron-stained root traces and ferruginized roots extend downward up to 40 cm into grey claystone from base of overlying ironstone bed. (B) Three closely spaced ironstone crusts, separated by thin ferruginous sandstones, cap a cycle of claystone containing isolated siderite nodules. (C) Uppermost ironstone crust from (B) displays a vesicular fabric consisting of interconnected voids and irregularly shaped intraformational clasts in a yellowish-brown ferruginous sandstone matrix. (D) Pisoliths with alternating light and dark layers are visible in slabbed sample of ironstone crust from middle of sequence in (B). Most pisoliths comprise multiple layers, but some consist of a single layer coating a clast. Scale divisions are in millimeters. (E) Sequence of finely interbedded claystone (grey) and mudstone with ferruginous sandstone lenticles near top of middle interval of prograding shoreface facies. Discontinuous to continuous nodular ironstone crusts thicken upward in sequence. (F) Float blocks of Naqb Formation rest on slope of uppermost shoreface mudstone-ferruginous sandstone cycles. The top of the section is visible at the top of the photograph where the Naqb Formation rests unconformably on the Bahariya Formation at the arrow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Features of fluvial facies associations. (A) Interbedded dark laminated mudstone and sandstone with ferruginous banding in the fluvial floodplain facies association, between the lower and middle intervals of prograding shoreface facies. (B) Planar cross-bedded sandstone interpreted as braided stream facies exhibits erosional relief where it cuts downward from left to right into underlying ironstone crust that caps the uppermost coarsening-upward cycle of the middle interval of prograding shoreface facies.

6.2. Petrography

Standard petrographic thin sections were prepared from samples of ferricrete and ferruginous sandstone from the Bahariya Formation at Gebel El-Dist. Ferruginous sandstones comprise a framework-supported assemblage of fine siliciclastic grains (nearly all quartz) and variable amounts of medium-sized grains of a yellowish-green to orange-brown mineral with yellowish-green

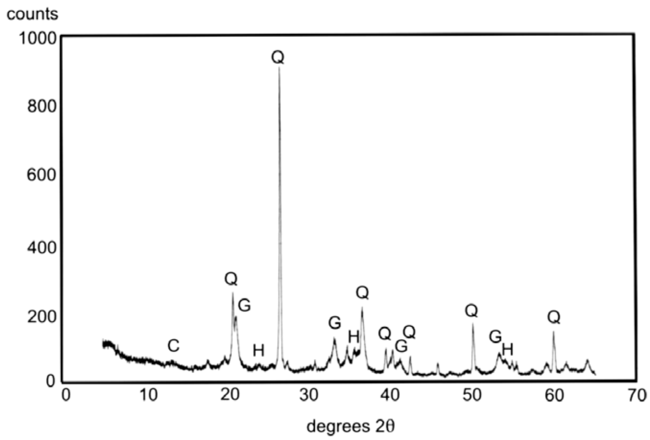

Fig. 6. X-ray diffraction pattern for representative sample of ironstone crust from the middle interval of prograding shoreface facies (the upper crust in Fig. 5B and C) with key diffraction peaks indicated for quartz (Q), goethite (G), hematite (H) and chamosite (C).

birefringence and little or no pleochroism (Fig. 8A). We interpret these as grains of glauconite that have undergone varying degrees of alteration to iron-oxide/hydroxide minerals (Mesaed, 2006). These grains constitute up to 50% of the volume of some sandstones, are irregular to rounded-oblate shape, and locally display brown rims, demonstrating partial alteration to an Fe-hydroxide such as limonite. Also occurring in some ferruginous sandstone beds are dark brown to opaque, coarse sand to pebble-sized dark ferruginous masses with distinct boundaries that we interpret as intraformational clasts. The ferruginous stain of the sandstones, which is uniform through thinner beds, but limited to the contacts on many thicker beds, is imparted by iron staining of matrix with a patchy distribution as well as by staining of a thin clay coating on the framework grains (Fig. 8A).

The ironstone crusts are distinguished from the ferruginous sandstone by the much darker rock colors (described above) and the presence of abundant (up to 70%) matrix that is dark reddish-brown (nearly opaque) in plane-polarized light (Fig. 8B). The particle size of the matrix is below resolution by optical microscopy and has no visible (i.e. asepic) fabric organization. In contrast to the ferruginous sandstones, the ironstone crusts commonly have a matrix-supported, rather than framework-supported fabric. Typically, the fabric lacks primary sedimentary layering, but instead may evidence disruption by invertebrate burrowing organisms and/or plant roots. This results in a patchy distribution of matrix and framework grains and burrows or plant roots, which form circular (in cross-section) concentrations of the iron-rich matrix (Fig. 8C). The framework grains range from well-sorted very-fine siliciclastic grains (primarily quartz) to approximately equal proportions of siliciclastic grains and larger (fine to medium-grain size) greenish-brown to orange-brown glauconite grains, as described above for the ferruginous sandstones. Large bivalve and gastropod shell fragments that have been largely replaced by hematite are common in many iron crusts and ferruginous sandstones (Fig. 8D). Many of the crusts have an irregular fabric characterized by the presence of intraformational ironstone clasts and pisoliths, up to 1 cm in diameter. In thin section, as well as in outcrop, the pisoliths generally display crude concentric layering with alternating light and dark bands, typically arranged in concentric to over-thickened cortical layers, and a central cavity (Fig. 8E). The clasts commonly are homogeneous, sub-round to angular and commonly contain silt to sand-sized detrital quartz grains (Fig. 8F). Detrital coatings on the exterior of some of the clasts demonstrates sedimentary reworking, possibly within the soil environment (Fig. 8F).

7. Discussion

7.1. Depositional environment of the ferricretes

El Aref et al. (1991) described ferricrete benches that cap the tablelands and inselbergs within the Bahariya depression. These ironstones occur at a similar elevation without regard to the stratigraphy, however, and are attributed to lateritic weathering on a

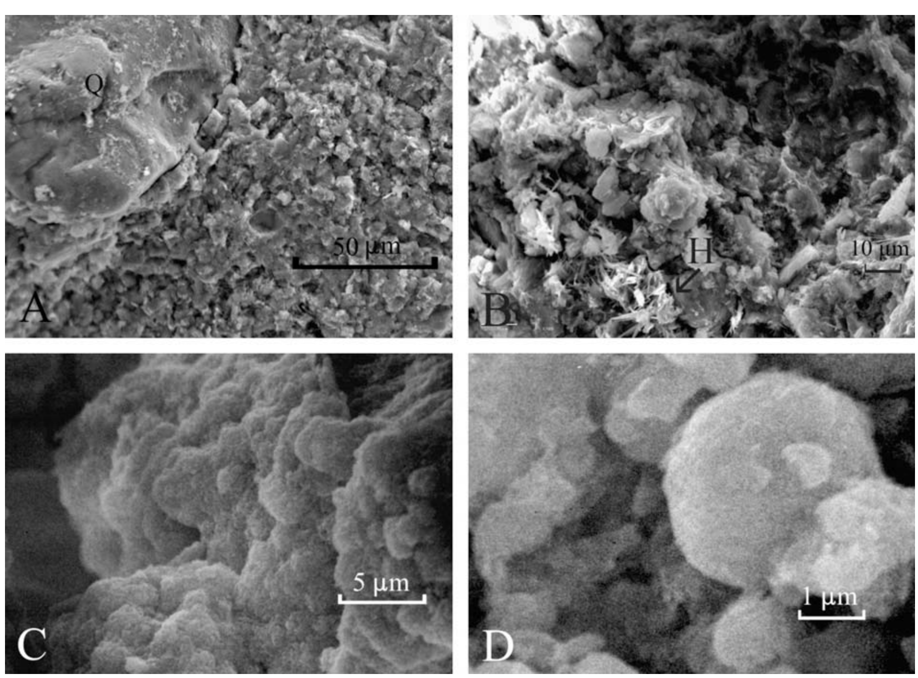

Fig. 7. Scanning electron microscopy of the ferruginous matrix. (A) Pervasive amorphous matrix in sandstone-hosted ironstone crusts consists of goethite filling pores between detrital quartz grains. (B) Well-crystallized hematite platelets (H) (after Welton, 1984) occur rarely in the goethite-rich matrix. (C) Mineral identified by X-ray diffraction as goethite (same sample as in Fig. 6) displays botryoidal to mammillary texture of crystallite aggregates. (D) Spherical aggregates, as in this example from the same sample as (C) may represent biomediated iron mineralization around bacterial cells, as suggested by El Aref et al. (2006b).

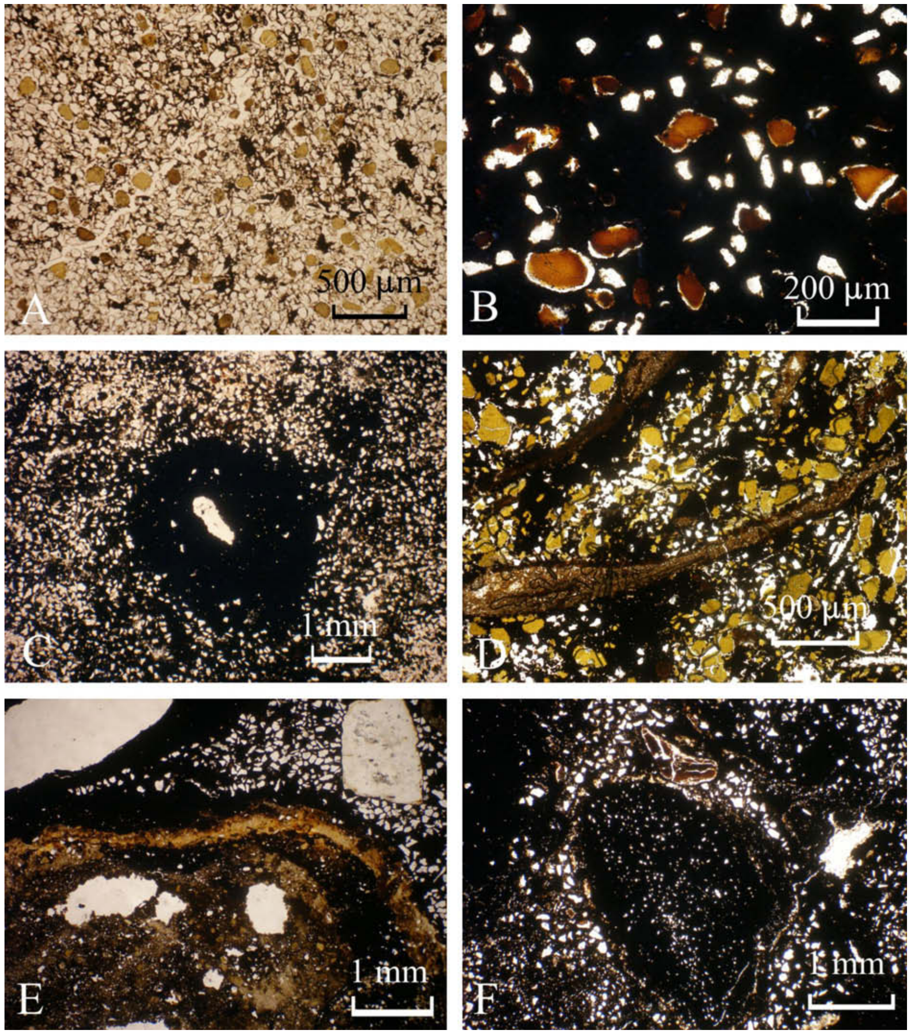

Fig. 8. Petrographic features of ferruginous sandstones and ferricretes from Gebel El-Dist. All photos taken with plane-polarized light. (A) Ferruginous sandstone from deltaic plain sandstones consists of mainly very-fine-grained, well-sorted framework siliciclastic grains and larger grains of glauconite. Grains are coated by ferruginous clay and there is a small proportion (~5%) of interstitial matrix. (B) Ironstone crust capping coarsening-upward shoreface cycle comprising 70% opaque matrix of goethite and 30% framework of siliciclastic and grains of partially altered glauconite. The glauconite grains are bordered by shrinkage voids formed by diagenetic dehydration. (C) Ferruginous matrix cements siltstone-hosted ferricrete. Root tubule (circular in cross-section) is filled by matrix, except for central channel. (D) Ironstone crust at top of coarsening-upward cycle in prograding shoreface facies displays ferruginized bivalve fossils, relatively unaltered, medium-sized grains of glauconite, very-fine-grained quartz and goethite matrix. (E) Ironstone crust containing large pisolith surrounded by very-fine-grained siliciclastics and argillaceous hematite matric. The pisolith displays alternating light and dark concentric layers (same sample as Fig. 4C). (F) Ironstone fabric displaying irregular distribution of matrix and framework grains, with large subrounded ironstone clast. The clast exhibits a higher percentage of matrix and finer siliciclastic portion than the surrounding matrix.

Tertiary erosional surface. The ferruginous lithologies distributed amongst the sedimentary facies in the Bahariya Formation are clearly unrelated to this later episode of laterization as most of the ironstone crusts at Gebel El-Dist occur as discrete facies-bounded beds within the coarsening-upward shoreface cycles. The fossil evidence supports the sedimentologic data in suggesting that the bulk of the Bahariya sediments accumulated in coastal environments. Bivalve (*Ostrea* and *Exogyra* spp.) and gastropod debris are common within these coarsening-upward cycles, mainly concentrated as lag deposits in the crusts. (Catuneanu et al. (2006) and Schweitzer et al. (2003) described a mangrove-dwelling crab from the lower part of the Gebel El-Dist section. The thin vertical traces in the mudstone (Fig. 3A) bear a striking resemblance to the well-known trace fossil *Skolithos*, typical of shallow marine trace fossil assemblages. Gregory et al. (2006), however, documented that certain plants, particularly those typical of paralic environments, such as mangroves, produce vertical root systems that can closely resemble *Skolithos* traces. This is consistent with the interpretation of Smith et al. (2001) of a marsh or vegetated tidal flat environment for portions of the formation, based in part on the presence of fossils of the mangrove plant *Weichselia* (see also Schweitzer et al. 2003). Thus, the sedimentologic evidence, in concert with the abundant but low diversity fauna, suggests that most of the ferruginous sandstones and ferricrete crusts formed in sediments that were deposited within an estuarine or lagoonal environment, potentially, in the sediments of intertidal sand flats or tidal deltas that formed the regressive caps to the coarsening-upward cycles.

7.2. Source of iron

Catuneanu et al. (2006) and Mesaed (2006) emphasized the presence of glauconite in the sediments of the Bahariya Formation, and attributed the formation of the ferricretes to the oxidation and release of iron during weathering. Mesaed (2006) in particular described progressive "hematization" of the glauconite grains in the sandstones of the formation as a result of weathering and concluded that this, in combination with alteration of a glauconitic matrix, provided the iron in the ironstones. We note, however, that many of the ferruginous sandstones contain both intact and relatively unaltered (i.e. green) glauconite peloids as well as patchy ferruginous cement. Moreover, most of the ironstone crusts we examined petrographically also contain intact unaltered or partially altered glauconite grains (Fig. 8A). Therefore, alteration of these grains could not have supplied the volume of iron present in the pervasive ferruginous matrix of the ironstones.

Alternatively, we consider the possibility that most of the iron was deposited with the primary sediment load. The Neoproterozoic basement complex presently exposed in the Nubian Swell to the south of Aswan (Thurmond, 2002) is a likely source area for the sediments of the Bahariya Formation. The location of this region near the palaeoequator during the Late Cretaceous ensures that this crystalline massif was subjected to conditions of intense weathering, thereby releasing an abundant supply of free iron. Furthermore, Floegel and Hay (2004) modeled the effect of the greenhouse climate, as would be predicted for the Late Cretaceous, on the hydrologic cycle and estimated that groundwater flow would be enhanced by up to six times present rates. This enhanced flow rate, combined with the comparable increase in iron availability to the hydrologic systems from enhanced chemical weathering, would have resulted in a substantially augmented delivery of iron to the Bahariya coastal water systems. This same process may have supplied the iron for the formation of the oolitic ironstone in the Upper Cretaceous Nubia Formation at Aswan (Bhattacharyya, 1989).

7.3. Formation of the ferricretes and ferruginous sandstones

Analysis of the pisolitic ferricretes by SEM revealed an iron mineral exhibiting a habit of crystallites forming aggregates with a mammillary to botryoidal morphology (Fig. 8C and D). El Aref et al. (2006b) observed similar structures in the Ghorabi ironstones and attributed these to biogenic processes of iron accumulation. Konhauser (1998) found that bacterially mediated iron mineralization may occur through a multi-step mechanism. Transition metal cations have a high affinity for negatively charged sites on cell walls and on biofilms, such as the extracellular polymeric substances produced by bacteria. These bound cations may then become nucleation sites for precipitation of ferrous iron when Eh conditions change. El Aref et al. (2006b) suggested that biofilms that coat grains during intervals of slow sedimentation later form ooidal/peloidal structures by recrystallization of Fe-colloids on these nucleation sites. The limited occurrence of these structures in the Bahariya ferricretes, however, suggests that this process was not as important in their formation as it was for the Ghorabi ironstones.

Catuneanu et al. (2006) and Khalifa and Catuneanu (2008) described the ironstone crusts in the prograding shoreface facies of the Bahariya Formation as ferricretes and attributed their formation to lateritic weathering of glauconite-bearing sediments in paleosol profiles. The presence of desiccation cracks and root traces were cited as evidence of subaerial exposure and soil profile formation. In their model, these paleosols were subsequently reworked by wave ravinement at the initiation of the subsequent cycle. As described by Tardy (1992) and Pickett (2003), the formation of an iron crust through pedogenic processes results in a distinctive profile that includes a mottled horizon and a bleached or pallid zone underlying the iron crust. However, only a few such profiles are present in the Bahariya Formation. Although some ironstone crusts occur above strata in which strong iron staining extends downward from the contact with the crust, most crusts occur as discrete accumulations of iron confined to a single bed, and these beds are often repeated at very close spacing (decimeters) within the section (Fig. 3F). Thus, there is a lack of recognizable vertical pedogenic profiles (i.e. with distinct A and B horizons) in the stratigraphic section. We note also that mangroves grow commonly in shallow subaqueous environments, and so the presence of their roots does not ensure subaerial exposure. Moreover, only brief subaerial exposure is required for formation of desiccation cracks. The presence of root traces and desiccation cracks does not imply sufficient exposure time for formation of a pedogenic profile and laterization. Additionally, the matrix fabric lacks any evidence of pedogenic organization (Fig. 8B).

Nonetheless, subaerial exposure of the ferricretes, as suggested by Catuneanu et al. (2006), is suggested in several ferricretes by the brecciation and pisolitization of the ferruginous matrix material, as these are processes which may occur in the soil environment due to repeated wetting and drying. This exposure was not necessarily contemporaneous with deposition of the sediment or the accumulation of the iron, however, and may record falling base-level subsequent to deposition and iron-enrichment of the iron cement. Truncation of one ferricrete by a non-ferruginous cross-bedded sandstone (Fig. 5B) indicates unambiguously that the iron accumulation occurred soon after deposition of the host sediment and was not a later diagenetic or metasomatic process.

The ferruginous sandstones we describe, particularly in the deltaic and floodplain facies, are incompletely cemented by iron and retain primary sedimentary structures. Bourman (1993) classified sandstones such as these, that are impregnated by groundwater-introduced iron, but still displaying primary sedimentary structures, as "ferricreted clastic sediments." Important to their recognition and interpretation is the fact that the accumulation of the iron is genetically unrelated to the underlying sediments. The iron mineral, mainly goethite, fills intergranular porosity and commonly replaces calcite in the bioclasts. Bourman (1993) described the impregnation of organic-rich sediments, or "ferricreted organic sediments," as forming iron bodies that commonly display a vesicular fabric in which the vesicles may be clay-filled or voids. We note the common association of plant roots with ferricretes in the shoreface cycles (e.g. Fig. 4A), and suggest that the voids we observe (Fig. 4C and D) formed as described by Bourman (1993). This author noted also that weathering of siderite-bearing siltstones and shales may form ferricretes with concretions with a central void. Similarly, we note that siderite is present in a ferricrete bed in which concretions and voids are prominent. Notably, Bourman (1993) maintained that the formation of these concretions is not a pedogenic process, but occurs through groundwater interaction. The presence of siderite is consistent with the interpretation that the muds were deposited in organic-rich lagoonal or estuarine environments.

Widdowson (2007) observed that multiple, or stacked ferricrete zones in profiles are not unusual, as the iron concentration is localized at the water table, which changes with time. Indeed, Goldbery and Beyth (1984) interpreted the multiple sheet crusts in the Triassic Budra Formation at Gebel Mussaba Salama as the record of still-stands in the rising water table on an aggrading alluvial plain. The iron is transported either in solution or as chelates by groundwater. Consequently, ferricretes are prone to form in areas of groundwater discharge, particularly swamps, estuaries and lake beds (Widdowson, 2007). Such a mode of formation is consistent with the occurrence of multiple, closely spaced ferricretes in the Bahariya Formation, particularly in the prograding shoreface facies association. As described by Widdowson (2007), allochthonous iron likely forms microcrystalline aggregates of oxyhydroxides that coalesce and gradually replace SiO_2 and $CaCO_3$, forming mottles, nodules and concretions, a process that is controlled to some extent by permeability. Therefore, iron cementation is preferential to bedding planes, as we describe in the Bahariya Formation.

Furthermore, Charette and Sholkovitz (2001, 2002) documented the concentration of ferrous iron in sediments below the sediment–water interface in an estuarine setting on Cape Cod, Massachusetts. These authors found that iron-oxide coatings formed on sand grains near the fresh groundwater–seawater interface through the oxidative precipitation of groundwater-derived ferrous iron. They further speculated that this subsurface interstitial precipitation of iron may be most common in settings where iron-enriched groundwater meets coastal waters. This model might also successfully explain the pervasive iron-enrichment of the sandstones capping the coarsening-upward sequences; in the shallow subsurface, these sediments were likely positioned for some time at the freshwater/marine water interface. Additionally, the concentration of iron at the contacts of the sandstones with adjacent clay or siltstone beds indicates that permeability was the controlling factor in the distribution of iron in these beds.

Consequently, we depart from the interpretation of Catuneanu et al. (2006) in attributing the iron accumulation solely to the processes of pedogenesis and laterization. We consider it more likely that the accumulation of the iron was largely the result of groundwater activity during early diagenesis and that the distribution was controlled primarily by sediment permeability. Therefore, we describe the ironstone crusts as ferricretes in the restrictive sense of Widdowson (2007) and other workers. The Fe-oxides and hydroxides accumulated in the shallow subsurface in the most permeable sediment layer, the sandstone at the top of each regressive cycle. In some instances, subsequent weathering of the sediment surface resulted in ablation and additional concentration of residual Fe-hydroxides to form iron hardpans. Prolonged intervals of exposure resulted in the formation of brecciated and pisolitic fabrics. Subsequent base-level rise initiated the next depositional cycle as the hardpan became a flooding surface. Hence, the ferricretes, to some degree, mark bounding surfaces in the stratigraphic sequence, although the ferricretes formed prior to surface flooding.

8. Conclusions

Ferruginous sandstones and ferricretes are a characteristic feature of the coastal strata of the Bahariya Formation. Ferruginous sandstones are iron-cemented sandstone beds in which primary sedimentary bedding is present. Typically, the cement is concentrated at the upper or both upper and lower contacts of the sandstone beds. Ferruginous sandstones are characteristic of the deltaic plain and fluvial floodplain facies associations. The ferricretes are ironstone crusts that typically cap coarsening-upward cycles in the shoreface facies association. These crusts display a range of textures that include rooted, massive, vesicular and pisoidal. Although some of the ferricretes exhibit evidence of sustained subaerial exposure, we discount a primarily pedogenic origin for most of the ironstone crusts. The accumulation of iron in both the ferruginous sandstones and ferricretes likely resulted from oxidative precipitation of iron-oxides in the subsurface during early diagenesis, either in the vadose zone, at the water table, or in the phreatic zone at the groundwater–seawater interface.

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