UPWARD-SHALLOWING SEQUENCES IN THE PRECAMBRIAN DUCK CREEK DOLOMITE WESTERN AUSTRALIA

by A. M. Thorne

ABSTRACT

Nine major sedimentary facies are recognized in the 2.0 to 1.7 Ga old Duck Creek Dolomite, which outcrops at Duck Creek Gorge in the western Pilbara. Markov Chain analysis demonstrates that these facies occur in repeated upward-shallowing sabkha-type sequences, among which offshore-barrier, lagoonal, intertidal, and supratidal deposits are recognized. These Proterozoic sequences are closely similar to the transgressive-regressive sequence of lithologies preserved in the Holocene sediment profile of Abu Dhabi, Arabian Gulf. A comparison of sequences from the upper and lower portions of the measured section at Duck Creek Gorge indicates that the coastal lagoonal complex became better developed with time. Small, branching-columnar stromatolites and large, branching-columnar stromatolites in the upper part of the section are interpreted as subtidal to shallow-intertidal forms. These, and tiny aborescent stromatolites that occur in the supratidal lithologies, are closely comparable to stromatolites reported from the 2.2 to 1.8 Ga old Rocknest Formation of Canada.

INTRODUCTION

Stratigraphy

The Duck Creek Dolomite is part of the Wyloo Group, an association of clastic carbonate and intermediate to basic volcanic rocks that outcrops in the Western Pilbara (Fig. 1). the Wyloo Group unconformably overlies the Fortescue, Hamersley, and Turee Creek Groups, and has an age of 2.0 to 1.7 Ga (Gee, 1980).

Pevious Work

No systematic studies of the sedimentology of the Duck Creek Dolomite have previously been undertaken. Daniels (1970) measured the succession at Duck Creek Gorge, recording colour, nature of bedding, and variation in abundance of stromatolites. Most interest in the Duck Creek Dolomite has concentrated on palaeontology. Edgell (1964), Grey (1979, 1982), Preiss (1977), and Walter (1972) studied stromatolites; and Knoll and Barghoorn (1975) recorded a gunflint-type flora from cherts in the upper levels of the formation.

Terminology

Intraclast: Fragment of penecontemporaneous, usually weakly consolidated, carbonate sediment that has been torn up and redeposited by current action.

Oncoid: A concentrically laminated sedimentary clast, which generally comprises alternating layers of blue-green algae and trapped carbonate sediment.

Grainstone: A mud-free grain-supported sedimentary carbonate rock.

Packstone: A grain-supported sedimentary carbonate rock which has a matrix of carbonate mud.

Fenestrae: Early diagenetic voids (larger than the grain-supported interstices) in the framework of a sedimentary rock. Laminoid fenestrae are elongate voids aligned parallel to the bedding.

Synoptic relief: In stromatolites, the relief of a stromatolite above its substrate at an instant of time during formation of the stromatolite.

FACIES DESCRIPTIONS

The succession of dolomites exposed at Duck Creek Gorge (lat. 22°28′39″ S, long. 116°19′25″ E) was examined in detail during the course of 1:250 000-scale remapping of the Wyloo area. The information presented in this paper was obtained by logging 220 m of particularly well-exposed dolomite at the eastern end of the gorge. In this part of the succession nine facies were recognized.

Facies A—intraclast grainstone

This facies outcrops in laterally persistent, tabular beds 5 to 100 cm thick (Fig. 2A). The upper and lower bedding surfaces are sharply defined, and the lower contact usually shows evidence of erosion. Little evidence of cross-stratification is preserved within these grain-stones, which may contain clasts up to 1.5 m across.

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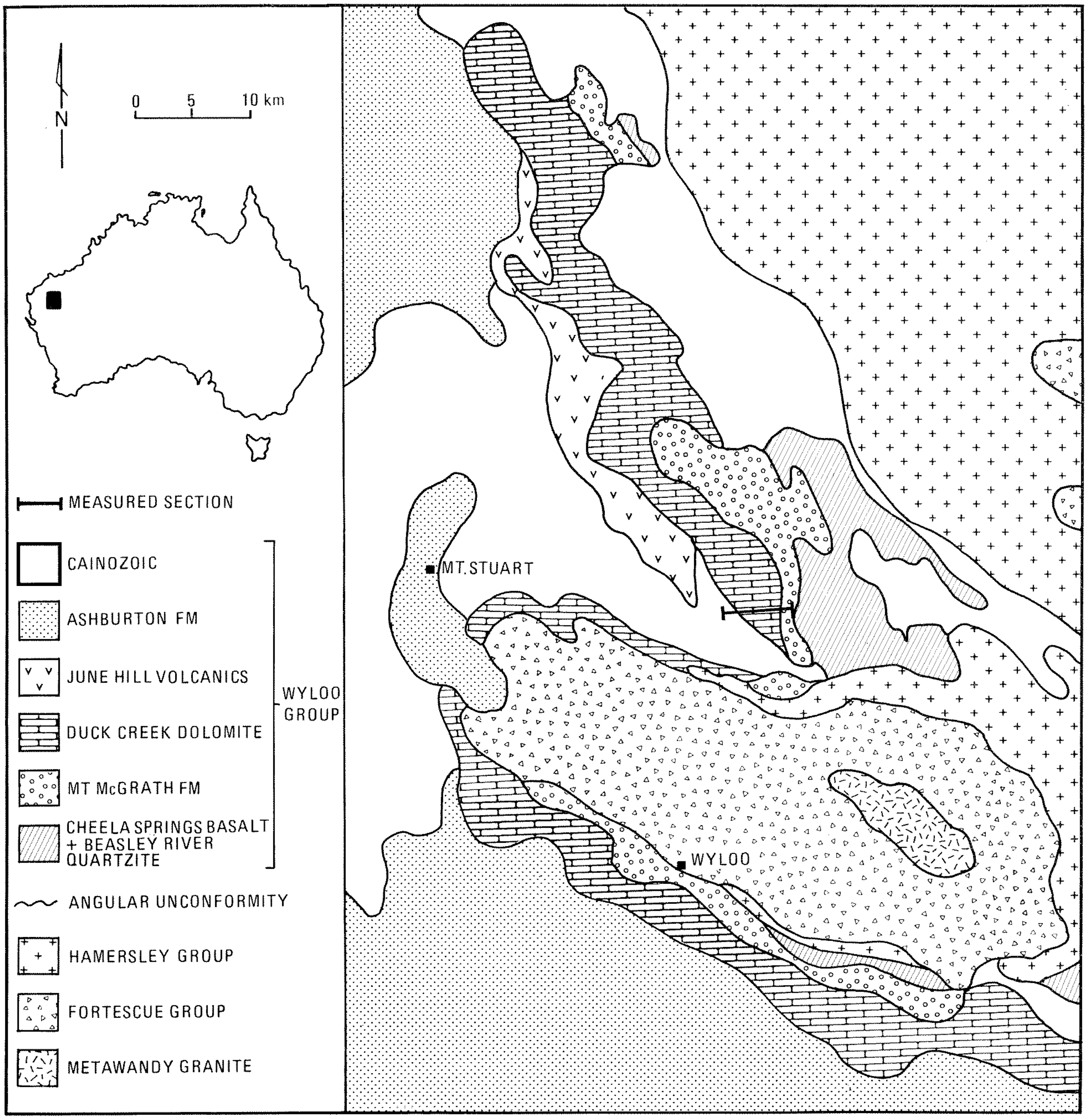


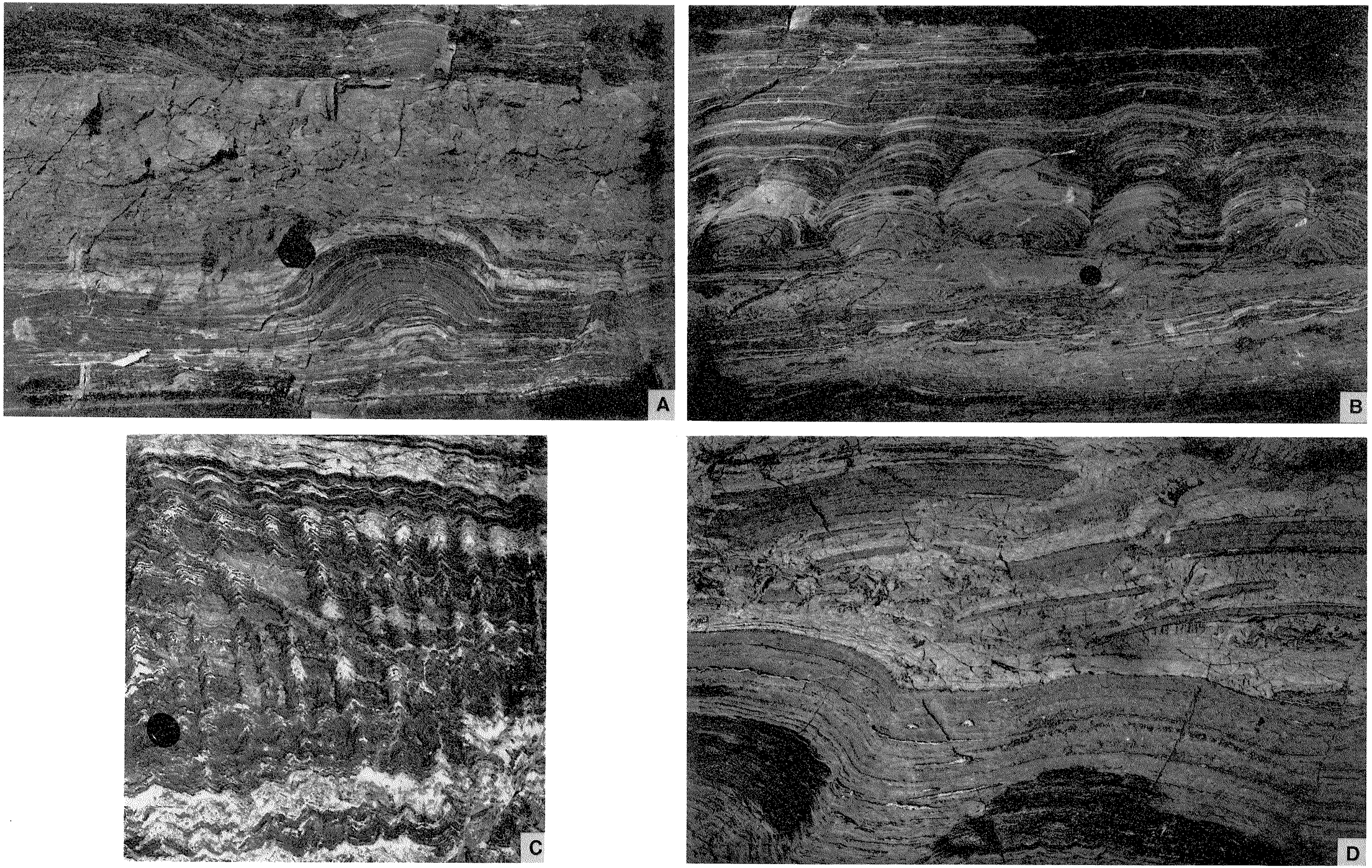
Figure 1. A geological sketch map of part of the western Pilbara, Western Australia.

Figure 2. A—A 25 cm-thick, erosively based intraclast grainstone overlying intertidal and supratidal dolomites. The grainstones, which rarely display any cross-stratification, are poorly sorted and may contain clasts up to 1.5 m across. This facies is interpreted as a transgressive barrier deposit.

B—Lagoonal, nucleated domical stromatolites overlying an intraclast grainstone containing a large imbricate clast (dipping gently to the left). The domical stromatolites are nucleated on pebble-sized oncoids and intraclasts, and the synoptic relief of the domes decreases upwards until they merge into the overlying intertidal laminated dolomite facies.

C—Highly silicified cuspate stromatolites showing the change to a convex form when traced upwards. Individual laminae either maintain constant thickness or vary in thickness when traced from peak to trough. These stromatolites were ridge-like and probably grew in a high-intertidal to supratidal environment.

D—High-intertidal to low-supratidal low domical stromatolites overlain by a very poorly sorted intraclast grainstone. The broad domes frequently comprise 1 to 5 cm layers of tiny aborescent stromatolites (field of view 1.5 m across).



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In thin section, the intraclasts are seen to be very poorly sorted and angular to well rounded. They are derived from pre-existing stromatolitic and grainstone deposits. The clasts are cemented by an early generation of fine- to medium-grained (20 to 200 μm) dolomite, and by later generations of coarse-grained subhedral dolomite and large, equant to bladed quartz crystals.

Facies B—nucleated domical stromatolites

Domical stromatolites nucleated on tabular oncoids and intraclasts are abundant within the Duck Creek succession (Fig. 2B). Usually the oncoid or intraclast nucleii are found as isolated clasts and give rise to spaced domical stromatolites whose synoptic relief decreases from about 10 cm at the base to zero at the top of the dome. The nucleii, particularly the oncoids, may occur in clusters; in which case, they form the cores of large, isolated domes up to 1.5 m across.

Facies C—laminated dolomite

This facies is characterized by planar to gently undulatory laminations and abundant laminoid or irregular fenestrae—now infilled by sparry dolomite, chalcedony, and coarsely crystalline quartz (Fig. 2B). Some laminae are disrupted by penecontemporaneous shrinkage cracks oriented normal to the bedding. Petrographically, two distinct types of laminae can be recognized. One type is marked by variations in the average size (5 to 250 μm) of the dolomite crystals. The finest grained laminae, in particular, are discontinuous and irregularly undulating. The second type of lamination is formed by sand-sized intraclasts that occur as laterally continuous layers 1 mm to 1 cm thick.

Facies D—cuspate stromatolites

Stromatolites in this facies display an irregular cuspate form with a synoptic relief of 1 to 3 cm, and a distance between peaks of 2 to 7 cm (Fig. 2C). Individual laminae either maintain a constant thickness or vary in thickness when traced from peak to trough. The stromatolite crests may merge upwards into convex forms. This stromatolite was probably ridge-like.

Facies E—low-domical stromatolites

These stromatolites show a gentle domical cross-section, 20 to 60 cm wide, with a synoptic relief of 3 to 10 cm (Fig. 2D). They have nucleated upon irregularities on the underlying substrate and exhibit two distinct forms of internal structure. One form is identical to the internal structure of the laminated-dolomite facies; the other form comprises 1 to 5 cm-thick layers of tiny aborescent stromatolites with close affinities to *Asperia* Semikhatov 1978 (Kathleen Grey, pers. comm., 1983).

Facies F—disrupted-domical stromatolites

These are bulbous stromatolite domes with relief up to 10 cm (Fig. 3A). The domes are characterized by having a core in which the original laminae are disrupted, and either partially or completely replaced by silica or coarsely crystalline dolomite. Many domes show evidence of penecontemporaneous erosion.

Facies G—tepee structures

In this facies, dolomite laminae have an irregular cuspate cross-section with an amplitude of a few tens of centimetres and wavelengths of up to 2.5 m (Fig. 3B). The anticlinal portions of the tepee are frequently brecciated and infilled by coarse detritus. The fact that the tepees are gradually overlapped by successively younger sediments, and often show evidence of penecontemporaneous erosion, demonstrates their synsedimentary origin.

Facies H—small, branching-columnar stromatolites

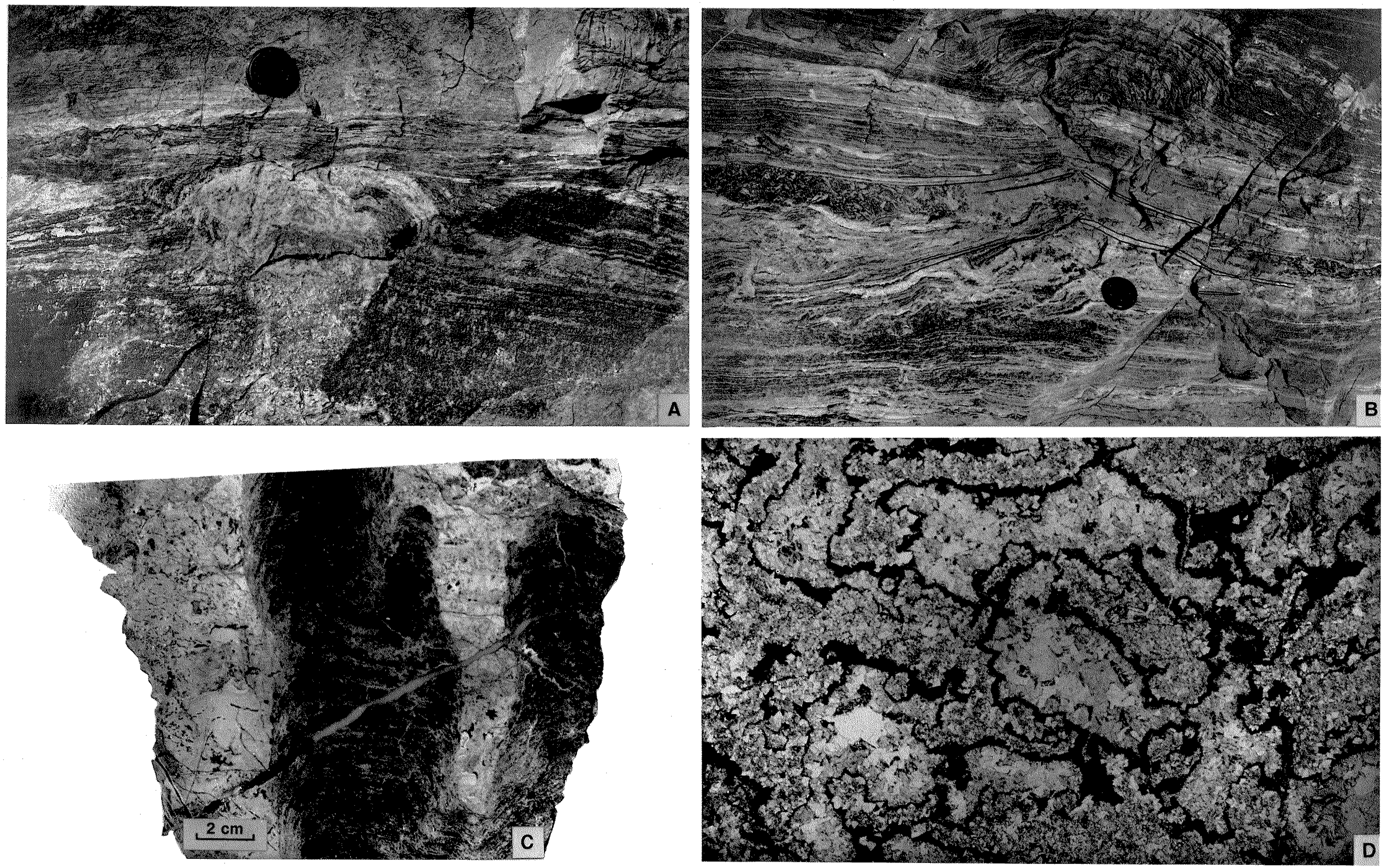
These stromatolites (*Pilbaria perplexa* Walter 1972) form continuous tabular biostromes 10 to 25 cm thick (Fig. 3C). The stromatolites are 2 to 5 cm wide, up to 25 cm high, and display an irregular style

Figure 3. A—The disrupted domical facies (supratidal). The lamination in the core of the small dome has been disrupted and is now replaced by coarsely crystalline dolomite and silica. This structure is closely similar to anhydrite diapirs reported from recent sabkha sediments of the Arabian Gulf. The planation surface truncating the dome may represent the effects of penecontemporaneous wind erosion.

B—The tepee facies (some of the bedding has been emphasised for clarity). The anticlinial portion shown here represents the buckled margins of broad polygonal structures formed by the repeated C—Part of the small branching-colomnar-stromatolite facies (lagoonal) showing the nature of the as a supratidal deposit.

C—Part of the small-branching-colomnar-stromatolite facies (lagoonal) showing the nature of the stromatolite morphology and internal structure. The stromatolites are the *Pilbaria perplexa* of Walter (1972). The interbranch areas are infilled by dolomitic intraclast packstone and grainstone.

D—Coarsely crystalline, subhedral to anhedral dolomite spar interpreted as a replacement after former anhydrite. The anhydrite is believed to have grown displacively within the original sediment, squeezing it aside until only vestiges remain. These vestiges are now represented by the thin, dark, finely crystalline dolomite walls.



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of branching in which individual branches do not maintain constant thickness. In addition, most stromatolite margins are embayed; and the internal laminae are steeply convex and may give rise to distinct walls. The area between branches is dolomitic intraclast grainstone or intraclast packstone, and is generally silicified.

Facies I—large, branching-columnar stromatolites

In this facies, the stromatolites occur in tabular units 50 to 200 cm thick (Fig. 3D). Stromatolite columns are usually 5 to 10 cm wide and sub-cylindrical in form with embayed walls. Some columns are coalesced or bridged, and most forms probably had a depositional relief of 5 to 25 cm. Unsilicified inter-column areas are infilled by dolomitic intraclast grainstones or intraclast packstones.

Fenestral dolomites

A feature commonly associated with facies C, D, E, F, and G, is the presence of irregular fenestrae, 1 to 20 cm wide, that cut across, disrupt, or merge with the original sedimentary layering. The fenestrae may contain disrupted relics of the original laminated dolomite, as shown in Figure 3D, or they may be composed entirely of coarsely crystalline, subhedral-to-anhedral dolomite cement; bladed to equant, subhedral-to-anhedral replacement dolomite; or coarsely crystalline quartz and chalcedony. The latter may show either length-slow or length-fast optical properties.

SEQUENCE ANALYSIS

An important consequence of Walther's Law of Facies-see Middleton (1973)—is that facies occurring in conformable vertical sequences were formed in laterally adjacent environments of deposition. This relationship provides the basis for interpreting the succession of facies observed at Duck Creek Gorge. Because of the large number of facies transitions recorded at this locality, the logged data were examined statistically to determine the most significant facies associations. The technique adopted for this purpose is based upon the embedded Markov Chain method (Powers and Easterling, 1982).

A sequence of lithologies is said to have a Markov property if it can be demonstrated that the occurrence of a particular facies is dependent upon the nature of the underlying facies—*e.g.* in a sequence of sediments it may be observed that a particular facies, say facies "P", tends to be followed by facies "Q" but not by facies "R" or "S". The transitions in a sequence of lithologies can be summarized in a matrix of one-step transitions; in Table 1 for example, the row A, column B entry in the matrix is the number of transitions

TABLE 1. Observed transition frequencies (Lower part of measured section).

	S	A	B	C	D	E	F	G	RT
S	0	6	9	3	0	0	0	0	18
A	12	0	4	8	1	0	1	0	26
B	0	4	0	10	0	3	1	0	18
C	3	8	3	0	1	5	5	2	27
D	1	1	0	2	0	0	0	0	4
E	1	2	0	3	2	0	1	0	9
F	1	3	1	3	0	0	0	0	8
G	0	2	0	0	0	0	0	0	2
CT	18	26	17	29	4	8	8	2	

S = Sharp contact
A = Intraclast - grainstone facies
B = Nucleated - domical - stromatolite facies
C = Laminated - dolomite facies
D = Cuspate - stromatolite facies
E = Low - domical - stromatolite facies
F = Disrupted - domical - stromatolite facies
G = Tepee facies
H = Small branching – columnar – stromatolite facies
I = Large branching – columnar – stromatolite facies
CT = Column total
RT = Row total

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TABLE 2. Estimated expected transition frequencies (Lower part of measured section). See Table 1 for key.

	S	A	B	C	D	E	F	G	RT
S	0.0	5.3	3.1	6.1	0.63	1.3	1.3	0.3	18
A	5.3	0.0	5.0	9.9	1.0	2.1	2.1	0.55	26
B	3.2	5.2	0.0	6.0	0.6	1.3	1.3	0.3	18
C	5.8	9.4	5.4	0.0	1.1	2.3	2.3	0.6	27
D	0.6	1.0	0.6	1.2	0.0	0.26	0.25	0.06	4
E	1.5	2.4	1.4	2.8	0.3	0.0	0.69	0.14	9
F	1.3	2.1	1.2	2.4	0.3	0.6	0.0	0.1	8
G	0.3	0.5	0.3	0.6	0.6	0.16	0.13	0.0	2
CT	18	26	17	29	4	8	8	2	

See Table 1 for key

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TABLE 3. Observed minus expected probabilities (Lower part of measured section). Only positive values shown. See Table 1 for key.

	S	A	B	C	D	E	F	G
S	0	0.04	0.43	0.17	-	-	-	-
A	0.26	-	0.04	0.08	-	-	-	-
B	-	0.07	-	0.23	-	0.1	-	-
C	0.1	0.05	0.09	-	-	0.1	0.11	0.05
D	0.1	-	-	0.2	-	-	-	-
E	0.06	0.05	-	0.03	0.19	-	0 04	-
F	0.03	0.12	0.02	0.08	-	-	-	-
G	-	0.75	-	-	-	-	-	-

See Table 1 for key

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from lithology A upwards into lithology B (this occurred 4 times). Because transitions from one facies into another bed of the same facies are not recorded, the matrix has the characteristic that the main diagonal frequencies must be zero. These values are referred to as structural zeros, and the sequence itself is termed an embedded Markov Chain.

More tests for a Markov property, *e.g.* Gingerich (1969) and Miall (1973), establish the Null Hypothesis that the sequence of facies transitions observed is random, a hypothesis which is tested using a Chi-squared statistic against an "independent trials" matrix. However, because matrices containing structural zeros cannot result from simple independent random processes, the above test is inappropriate. In particular, the "independent trials" (or expected transition frequencies) should be calculated taking into account the presence of the structural zeros. This problem can be resolved by various statistical techniques (Carr, 1982; Powers and Easterling, 1982). The method adopted for this work is based upon that of Powers and Easterling (1982) and employs a model of quasi-independence to overcome the problem of structural zeros in the transition matrix.

The logged section at Duck Creek Gorge can be divided into two halves on the basis of the distribution of facies types. In the following analysis, the presence of five small gaps in the complete sequence was ignored, although it is recognized that they probably add a small random component to the sequence of facies. It should also be noted that sharp facies contacts are shown in the transition matrices (Tables 1-3). All other contacts are gradational except for the base of the intraclast-grainstones facies, which is always sharp and erosive.

Lower half of logged section

Table 1 shows the observed facies transitions in the lower part of the Duck Creek Gorge section. Table 2 gives an estimate of the expected transition frequencies using a model of quasi-independence. Testing the fit of the quasi-independent model yields $\chi^2 = 73.5$ a value which would be expected less than once in 200 times (with forty-one degrees of freedom) if a Markov process were not operating. There is thus considerable evidence against the assumption of quasi-independence, and the facies associations in this part of the succession are shown to have a strong Markov property.

We can now ascertain which of the facies transitions are the most significant. This is achieved by converting the observed and expected frequency data in the matrices into probabilities (these values are obtained by dividing the value of a particular element in the matrix by the appropriate row total). The expected probabilities are then subtracted from the observed probabilities, and the highest positive values that remain (those greater than 0.1) constitute the most significant transitions (Table 3).

The most significant transitions are summarized in Figure 4, where it can be seen that the most preferred sequence, repeated throughout this lower part of the section, is one which shows an intraclast-grainstone base, overlain by a sharp contact, which is, in turn, succeeded by nucleated domical stromatolites and then by the laminated-dolomite facies. From here the sequence passes upwards into one or several of the following facies, tepee, disrupted-dome, cuspate-stromatolite or broad-domical-stromatolite before being overlain by the next erosively based intraclast grainstone. This sequence, designated "Preferred Sequence 1", is shown diagrammatically in Figure 5.

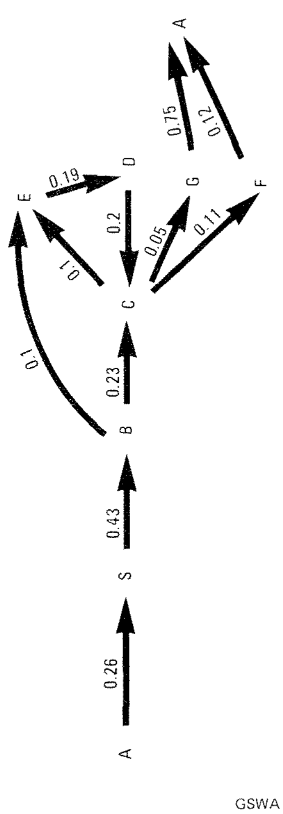

Figure 4. Facies-relationship diagram showing the most significant transitions (lower part of measured section) *See* Table 1 for key.

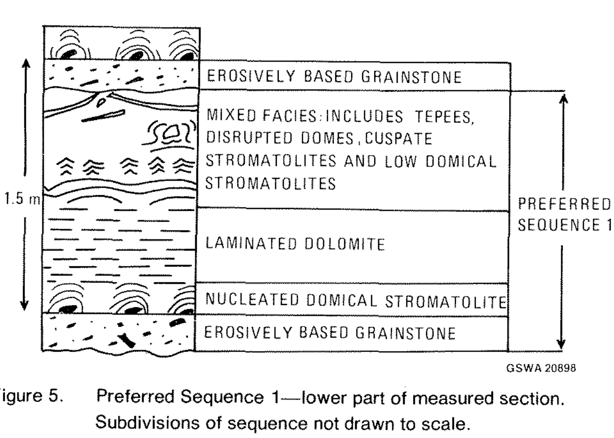

Figure 5. Preferred Sequence 1—lower part of measured section. Subdivisions of sequence not drawn to scale.

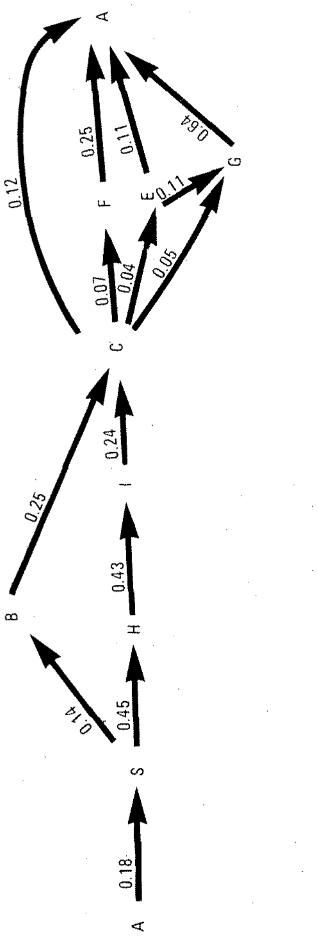

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Figure 6. Facies-relationship diagram showing most significant transitions (upper part of measured section). *See* Table 1 for key.

Upper half of logged section

The uppermost part of the measured section was also analyzed by the statistical method outlined earlier. The strong Markov tendency present in the lower part of the section is even more pronounced in the upper part. Testing the fit of the quasi-independent model yields $\chi^2 = 156$, a value which could be expected less than once in 1000 times (with 55 degrees of freedom) if a Markov process were not operating. The more significant transitions in the upper part of the section are shown in Figure 6, and the most preferred repeated sequence is characterized by a basal intraclast grainstone overlain by a sharp contact, which is followed, in most cases, by small, branching-columnar stromatolites then by large, branching-columnar stromatolites, which are overlain by laminated dolomite. From here the sequence passes back into the erosive grainstone either directly or through the tepee, low-domical-stromatolite, or disrupted-domical-stromatolite facies. The complete sequence, designated "Preferred Sequence 2", is shown diagrammatically in Figure 7.

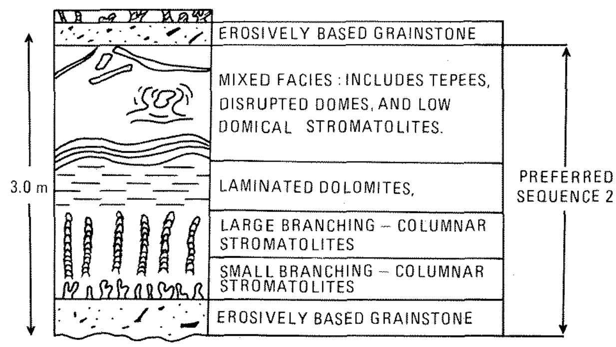

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Figure 7. Preferred Sequence 2 (upper part of measured section). Subdivisions of sequence not drawn to scale.

A RECENT ANALOGUE

The various facies and facies sequences outlined in the previous sections are most easily interpreted by comparing them with the coastal deposits of the Trucial Coast, Arabian Gulf.

The morphology of Holocene sediments of the Trucial Coast was studied by numerous workers during the 1960's and 1970's; the results of many of these studies were presented by Purser (1973) and summarized by Till (1978). Briefly, the coastal strip, which is up to 40 km wide in the vicinity of Abu Dhabi, has a complex outer barrier zone of offshore islands, channels and tidal deltas, separated from the mainland by a lagoonal system. Landward of the lagoonal complex is a zone of intertidal algal flats which pass imperceptibly into a dessicated supratidal plain or sabkha. The sediments associated with the outer barrier system are composed of ooids, skeletal sand, and lesser amounts of coral/algal reef material; but the lagoon is characterized by muddy sands and coarser detrius in the lagoonal channels. The intertidal flats are colonized by blue-green algae, which trap sediment and show a variety of algal-mat forms, the morphology of which is controlled by the frequency of storm-driven flooding events. The sabkha surface contains carbonate sediments deposited by exceptional storm events. However, the characteristic feature of the sabkha is the occurence of early diagenetic nodular anhydrite, gypsum, celestite, and ephemeral halite. The growth of anhydrite layers within the sediment (they may constitute half the thickness of the supratidal sediment profile) results in a raising of the sabkha surface: this is balanced by wind deflation and erosion caused by storm flooding.

Stratigraphy of Holocene deposits

The lateral distribution of the surface environments described above is mirrored in the Holocene sediment profile of the coastal sabkha zone; this distribution is due to a marine transgression and regression which occurred during the past 5 000 years. During the initial Holocene transgression, sedimentation rates were too slow to keep pace with the retreat of the shoreline,

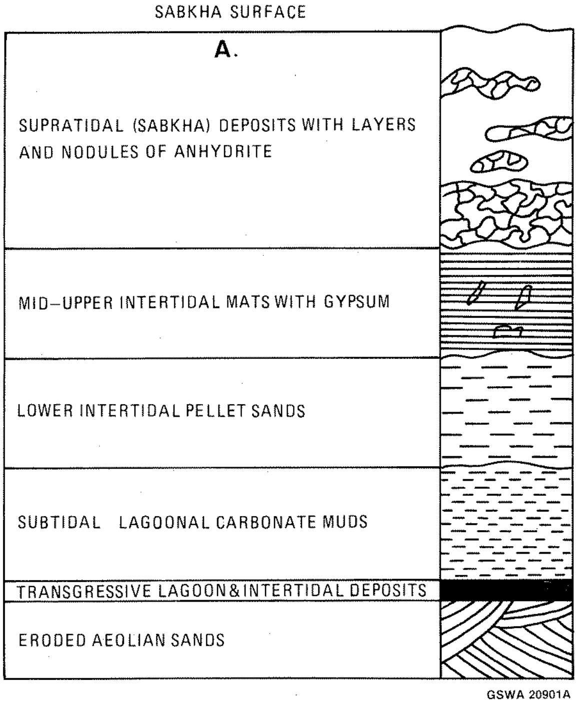
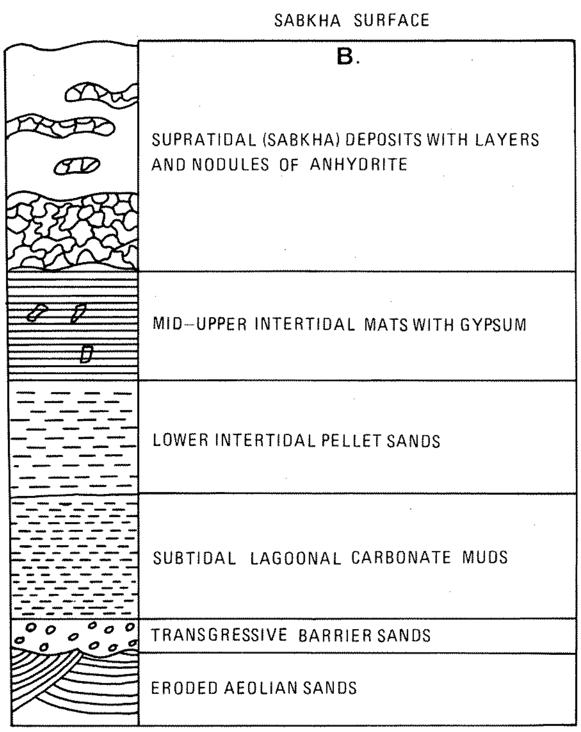


Figure 8. A—Diagrammatic representation of the upward-shallowing sabkha sequence from Abu Dhabi (modified from Till, 1978).



B—Diagrammatic representation of an "ideal" upward-shallowing sabkha sequence.

and only a 10 cm sequence of transgressive subtidal and intertidal sediments is preserved. Subsequent regression, caused mainly by sediment offlap, together with a 1.2 m drop in sea level, has resulted in the deposition, above the transgressive deposits, of up to 4 m of regressive subtidal, intertidal, and supratidal sediments (Fig. 8A). This profile represents one type of upward-shallowing sequence (James, 1979) and could readily have been predicted by applying Walther's Law of Facies to the association of sedimentary environments displayed in this area.

The sequence of lithologies shown in Figure 8A is to some degree incomplete because it does not record the presence of the offshore-barrier deposits. During the Holocene transgression, these sands did not advance as far as the present day sabkha zone. Had this transgression migrated far enough inland, the sabkha profile would be expected to show the complete sequence of barrier, lagoonal, intertidal, and supratidal deposits shown in Figure 8B.

PALAEOENVIRONMENTAL INTERPRETATION

Preferred Sequence 1

Figure 9 compares the ideal sabkha sequence from the Trucial Coast with Preferred Sequence 1 from Duck Creek Gorge. The erosively based grainstone that occurs at the bottom of Preferred Sequence 1 is equivalent to the ooid and skeletal-sand horizon of the ideal sabkha sequence, and represents the remnants of a transgressive offshore barrier system. The largest clasts occurring within the Precambrian intraclast grainstone are derived from (at least partially) lithified lagoonal, intertidal, and supratidal deposits. As discussed by Kraft (1971), a thin transgressive record, such as occurs in both the Duck Creek Gorge and Trucial Coast sequences, points to a slow rise in relative sea level, because such a slow rise allows shoreface erosion to remove most of the retreating shoreline sediments soon after deposition.

The thin (1 to 5 cm) layers of intraclast grainstone that occur randomly within the sequence are interpreted as storm deposits. Park (1976) notes the storm sedimentation is probably the single most important depositional process in the intertidal zone of the Trucial Coast; sediment layers greater than about 1 cm in thickness are attributed to storm activity which was sustained for several days.

The nucleated-domical-stromatolite facies is interpreted as a subtidal lagoonal deposit despite the fact that it apparently has no exact counterpart in the recent sediments of the Arabian Gulf. Kinsman and Park (1976) record small, gelatinous, isolated domes associated with bioclastic muddy sands in some Trucial Coast lagoons. Those stromatolites, however, differ in detailed morphology and internal structure from the domes at Duck Creek Gorge. More closely analogous to the Precambrian domical stromatolites are the subtidal forms reported by Gebelein (1976), from Florida, the Bahamas, and Bermuda, where the stromatolites grow up to 10 cm high and 30 cm wide and are associated, particularly in the moderately agitated environments, with oncoids.

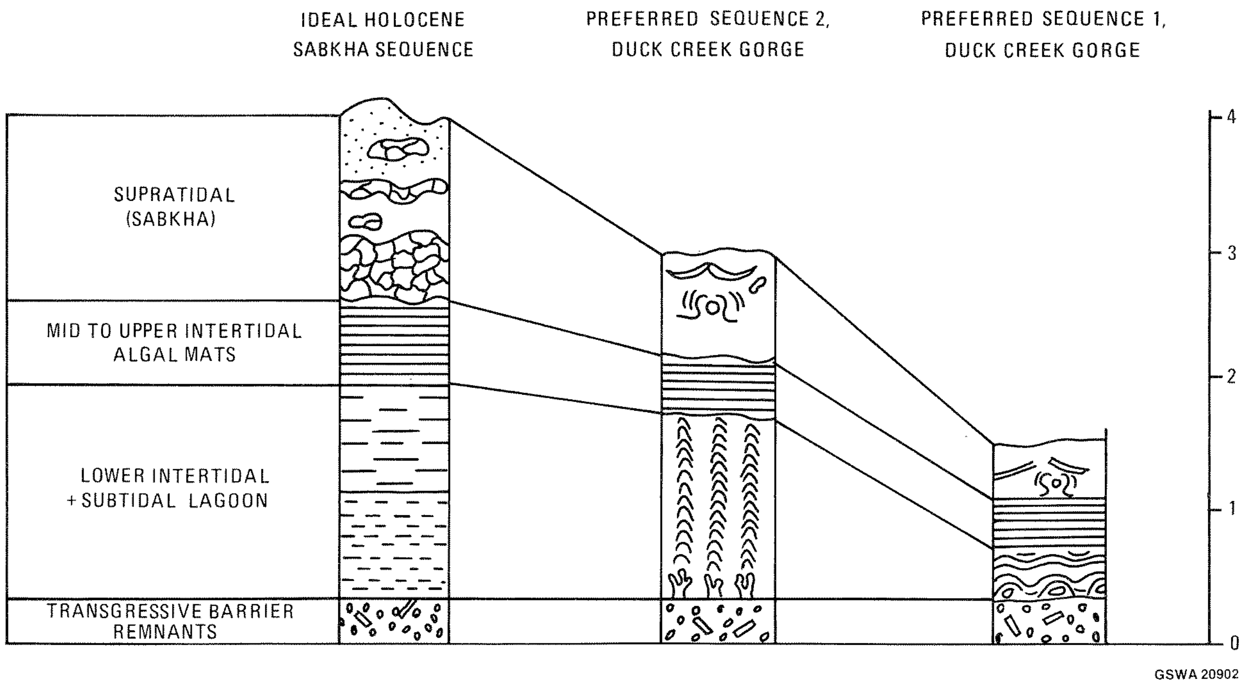


Figure 9. A comparison of lithologies and thicknesses between an ideal Holocene sabkha sequence and Preferred Sequences 1 and 2 from Duck Creek Gorge.

The laminated-dolomite facies, which overlies the nucleated-domical-stromatolite facies, is closely analogous to the laminated middle intertidal sediments of the ideal sabkha sequence. Park (1976) describes how these Recent laminites consist of alternations of blue-green algae and layers of trapped sediment, many of the latter being deposited during storm events. Rotting of the algal layers gives rise to the development of irregular laminoid fenestrae; however, if the decay is accompanied by dehydration, compaction, and lithification, thin layers of finely crystalline carbonate would result instead (Park, 1977).

The low-domical-stromatolite, cuspate-stromatolite, disrupted-domical-stromatolite, and tepee facies, are grouped together as a zone of mixed facies equivalent to the high-intertidal and supratidal portion of the ideal sabkha sequence.

The cuspate stromatolites and low domical stromatolites have no precise analogue in the Recent sediments of the Arabian Gulf. The cuspate stromatolites are loosely comparable with the pinnacle algal mat described by Park (1976) from high-intertidal environments on the Trucial Coast, though these Recent stromatolites apparently do not develop a ridge-like morphology. As described previously, the internal structure of the low domical stromatolites is often closely similar to that of the laminated dolomite facies, which is interpreted as an intertidal deposit. These domes, which occur above the laminated dolomites in the preferred sequence, are therefore likely to be a high-intertidal form. Low domes whose internal structure is characterized by layers of tiny aborescent stromatolites are more problematical. These forms possibly represent stromatolite growth in laterally restricted, hypersaline pools on the very high-intertidal of supratidal surfaces.

The tepee structures, diagnostic of facies G, represent the buckled margins of large polygonal structures formed in the supratidal zone by the dessication, wetting, cementation, and mechanical fracturing of sediment layers (Assereto and Kendall, 1977).

Relic evaporite textures and mineralogies

A characteristic feature of modern sabkha sequences is the association of evaporite minerals, notably gypsum and anhydrite, with dolomitized algal-laminated sediments. The diagenesis of these evaporite minerals can be particularly complex; they are commonly subject to recrystallization and solution, and replacement by a variety of minerals. No occurrences of evaporite minerals have yet been found in the Duck Creek Dolomite; however, evidence in the form of relic textures and replacement minerals points to their former widespread development.

Structures closely comparable with the disrupted domical stromatolites of facies F are reported to be forming just below Recent sabkha surfaces and result from the displacive growth of anhydrite within the sediment; this often leads to the formation of small anhydrite diapirs (Shearman 1980).

As described earlier, facies C, D, E, F, and G (all interpreted as being intertidal or supratidal in origin) often contain irregular fenestrae (1 to 20 cm wide) that cut across, merge into, or disrupt the sedimentary layering. The internal structure of some of those fenestrae (fig. 3E) is very similar to the chicken-wire texture resulting from the growth of anhydrite (often as a replacement after gypsum) in Recent sabkha profiles. In many of the dolomites from Duck Creek Gorge, the original evaporite mineral has apparently undergone *in situ* replacement by anhedral dolomite spar. In other cases, the replacement dolomite occurs as small rosettes or layers of subhedral bladed crystals. The large anhedral to subhedral quartz crystals and chalcedony that infill many fenestrae are commonly found as replacements after evaporites in ancient sabkha sequences. Chalcedony that is optically length slow is, in particular, regarded as a reliable indicator of original evaporite minerals (Folk and Pittman, 1976).

The above comparison between Preferred Sequence 1 from the lower part of the Duck Creek Gorge section and the ideal sabkha sequence shows that they are similar, both in the types of lithology present and in the vertical distribution of these lithologies. From this evidence, the lower part of the Duck Creek Gorge section can be interpreted as comprising numerous upward-shallowing sequences caused by repeated marine transgressions and regressions across a sabkha-type coastline.

Preferred Sequence 2

Preferred Sequences 1 and 2, obtained from the lower and upper parts of the Duck Creek Gorge section respectively, are similar both in the type of lithology and in the vertical arrangement of these lithologies. On this basis, Preferred Sequence 2 is also interpreted as being an upward-shallowing sabkha-type sequence.

A characteristic feature of Preferred Sequence 2 is the presence of layers of small branching-columnar stromatolites and large, branching-columnar stromatolites, which occur between the basal intraclast-grainstone facies and laminated-dolomite facies—*i.e.* in place of the nucleated-domical-stromatolite facies. Small branching-columnar and large, branching-colunmar stromatolites, comparable to those found at Duck Creek Gorge, have not been recorded in Recent sedimentary environments. Columnar stromatolites presently found in subtidal settings at Shark Bay (Playford and Cockbain, 1976) are loosely comparable to the Duck Creek Gorge examples in their general form but differ markedly in details of internal and external structure.

In the absence of any suitable modern analogue, we have to rely on the position of the small branching-columnar and large, branching-columnar-stromatolites in the upward-shallowing sequence to provide evidence concerning their original environment of deposition. As shown in Figures 7 and 9, the stromatolitic facies in question are found above the intraclast-grainstone facies (the remnants of the transgressive barrier deposit) and below the intertidal laminated-dolomite facies. This would indicate that the small, branching-columnar-stromatolite facies is a subtidal lagoonal deposit whereas the large, branching-columnar-stromatolite facies was formed in a subtidal-lagoonal to shallow-intertidal setting.

DISCUSSION

As shown in Figure 9, Preferred Sequence 2 and the ideal sabkha sequence from the Trucial Coast are of comparable thickness; the slightly greater development of the Recent sequence is attributed to the fact that this profile has undergone little compaction. Preferred Sequence 1 is, on average, 1.5 m thick, approximately half the thickness of the other two sequences, and most of the difference is due to the poor development of the lagaoonal to lower intertidal portion of this sequence. The thickness of the subtidal-lagoonal portion of the upward-shallowing sequence (prior to compaction), largely reflects the depth of the original lagoon. This indicates that the lagoonal complex, poorly developed in the early history of this shoreline, became deeper and probably wider with time. This environment, with its higher wave energies (and possible tidal channels), was apparently a favourable setting for the growth of the small, branching-columnar and the large, branching-columnar stromatolites found in the upper part of the measured section.

In many coastal sabkhas of the Abu Dhabi region, zones of nodular anhydrite make up at least half the thickness of the supratidal deposits (Shearman, 1980). Relic evaporite textures present in the Duck Creek Dolomite, however, form only 10 to 15% of the supratidal lithologies. Even allowing for the fact that some of the evaporites originally present in the Duck Creek Dolomite may have vanished without trace during erosion or diagenesis, it is unlikely that they were ever quite as extensive as they are in the present-day coastal sabkhas of the Trucial States. This would indicate that a cooler, possibly more humid climate than presently occurs in the Arabian Gulf, prevailed in the Pilbara region during deposition of the Duck Creek Dolomite. No evaporite relics have yet been recorded from the subtidal portions of the Precambrian upward-shallowing sequences. This suggests that the ancient sabkha-type coastline bordered on an ocean whose salinity was equal to or slightly higher than that of presently normal marine waters (Kendall, 1979).

No satisfactory explanation can be given to account for the history of repeated marine transgressions recorded in the Duck Creek Gorge section. Kendall (1979) and White (1981) discuss possible mechanisms for producing repeated transgressions in other carbonate successions—*e.g.* tectonic subsidence or sea level changes induced by glaciations or global tectonism. Any one of these mechanisms acting alone, or in combination, could account for the repetition of upward-shallowing sequences observed in the Duck Creek Dolomite.

Comparisons with other ancient examples of upward-shallowing sequences

Many examples of upward-shallowing sabkha-type sequences are preserved in the geological record, and most are recorded from Phanerozoic successions—*see* summary by Till (1978). Published accounts giving details of this type of sequence in Precambrian rocks are less common. Hoffman (1976) describes the occurrence of almost 200 upward-shallowing sequences in the 2.2 to 1.8 Ga old Rocknest Formation of the Canadian Shield. These sequences differ from those described in this study in that the regressive deposits grade from offshore marine to intertidal sand flats without any intervening barrier or lagoonal sediments. In addition, Hoffman (1976) does not record the presence of relic evaporite textures in any supratidal deposits. Tiny aborescent stromatolites, similar in form to those occurring in the supratidal horizons of Duck Creek George succession, are recorded in equivalent facies in the Rocknest dolomites. Columnar stromatolites closely comparable to those described in this study are, in the Canadian succession, restricted to the low-intertidal facies. White (1981) reports on upward-shallowing sequences in the 1.45 Ga old Altyn Formation of Montana, U.S.A. As with the Rocknest Formation, these sequences do not record any barrier or lagoonal facies; they do, however, contain replacement evaporite textures and minerals in the supratidal deposits.

CONCLUSIONS

This work provides further evidence for the existence of upward-shallowing sabkha-type sequences in the Precambrian sedimentary succession. The association of particular stromatolite morphologies with distinct environments of deposition points to a strong environmental control on their gross morphology. Detailed features of morphology and internal structure, however, might well be the result of biological factors. The "sequence approach" to interpretation used in this study may provide a rigorous method of demonstrating possible evolutionary trends in stromatolites, because forms of differing age and varied location that grew in similar environments of deposition can now be compared.

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