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SELECTIVE CEMENTATION OF EOLIAN STRATIFICATION IN PLEISTOCENE CALCARENITES, SAN SALVADOR ISLAND, BAHAMAS

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ABSTRACT

Subdivisions of the Grotto Beach Formation, such as the French Bay Member and eolian beds in the Cockburntown Member, comprise part of the Pleistocene interval of fossiliferous, peloidal oosparite or calcarenite exposed on southern San Salvador Island. Stratification is typified by complex crossbeds consisting of sandflow and local grainfall foresets and wind-ripple strata. Each stratification type is characterized by specific grain size, packing, and pore size inherited from eolian subprocesses such as sandflow, grainfall and ripple migration. These grain textures have controlled the degree of fluid adhesion and capillarity which have affected the degree of cementation within each stratum. Climbing wind-ripple strata are recognized in outcrop by thin, even laminations which locally exhibit inverse grading. Both outcrop exposures and thin sections are typified by pairs of lamina-sets consisting of alternating positive-relief "micro-ledges" and negative- relief "micro-recesses". A "micro-ledge" forms the lower part of a wind-ripple stratum and consists of moderately to tightly packed, well-cemented fine sand among which the pores have been completely cemented with interlocking equant crystals of low-magnesium calcite. The upper part of a ripple stratum forms a "micro-recess" composed of moderately to loosely packed, poorly cemented fine medium sand. Sandflow beds show a two-fold segregation of fine sand in the basal few millimeters and medium sand in the upper few centimeters in each bed in outcrop and in thin section. The basal fine layers are characterized by moderate to tight grain packing and small pores. The pores are completely filled with interlocking equant crystals of low-magnesium calcite such that the basal laminations form positive-relief "micro-ledges" in weathered outcrops. The upper part of a sandflow bed is composed of moderately to loosely packed medium sand with large pores which have been incompletely filled with isopachous and meniscus cement. Consequently, negative-relief, "micro-recess"-forming beds distinguish upper sandflow beds from other strata. Grainfall strata were not examined in this study.

INTRODUCTION

General Statement

In their pioneer studies of quartzarenites, Huntington (1907), Knight (1929), and McKee (1934a,b) distinguished physical aspects of cross-bedding which supported an origin by migration of ancient eolian dunes. Since then, the recognition of specific eolian stratification types or fine structure (Hunter and Rubin, 1985) within cross-bedded sets of quartzose sediments (Hunter, 1977a,b) and sandstones (Hunter, 1981) has greatly enhanced the ability of sedimentologists to discriminate eolian from subaqueous stratification. Later studies have defined fine structure in the interpretation of some Paleozoic and Mesozoic eolian sandstones in the Western Interior (Kocurek and Dott, 1981; Blakey and Middleton, 1983; Loope, 1984; Porter, 1987; Caputo, 1988) and other parts of the world. Despite the fact that wind-blown limestones (cf. eolian calcarenites or eolianites) have been recognized since the turn of the century (Evans, 1900) in various tropical and subtropical parts of the world (Ball, 1967; MacKenzie, 1964a,b; Ward, 1970, 1973, 1975; McKee and Ward, 1983), distinctive eolian stratification has only recently been described in Holocene (White and Curran, 1985, 1986, 1988), and Paleozoic (Loope, 1986; Hunter, 1988) eolian limestones.

Purpose

This report presents preliminary observations and interpretations of eolian bedding styles preserved in intervals of the Pleistocene Grotto Beach Formation, namely the French Bay Member, and eolian beds in the Cockburntown Member, on southern San Salvador Island. The report will attempt to bridge the gap between studies on siliciclastic eolian deposits and eolian limestones and describe a relationship between eolian processes, grain characteristics, and cementation patterns which are expressed in different weathering patterns in outcrop. The following ideas are presented in the report: 1. Specific bedform subprocesses such as sandflow, grainfall, and the migration of ripples in a general wind-blown environment do indeed operate for carbonate grains. 2. These subprocesses produce sandflow, grainfall and ripple strata in carbonate sediment which are similar to those in siliciclastic eolian deposits. 3. These strata are characterized by different grain sizes and packing which are inherited from bedform subprocesses. Furthermore, the inherited grain size and packing have controlled fluid capillarity between grains and subsequent cementation patterns. 4. The grain-cement relationships are expressed by different weathering patterns in outcrop. 5. Weathering patterns which are associated with specific eolian stratification types can be used to identify sandbody architecture in outcrops.

Location and Stratigraphic Setting

San Salvador is one of a series of emergent island platforms of the Bahamian Islands (Index map 1). It consists entirely of late Pleistocene and early to late Holocene, cemented, skeletal and oolitic carbonate rock.

Outcrop examples of eolian stratification and petrographic examples of grain texture, fabric, and cementation are selected from the Pleistocene Grotto Beach Formation. This unit comprises part of a well- exposed, significantly thick stratigraphic interval in the upper Neogene System of rocks on San Salvador Island (Fig. 1). The development of stratigraphic intervals and nomenclature for this locality is given in Carew and Mylroie (1985). The French Bay Member, Cockburntown Member, and Dixon Hill Member compose the Grotto Beach Formation in ascending order (Fig. 1). Physical sedimentary features and stratigraphic relations suggest an eolian origin for the lower and upper members and marginal marine and eolian affinities for the middle Cockburntown Member. The French Bay Member forms gray, wave-battered seacliffs which armor the shore south of Grotto Beach, around the Sandy Point headland, and along part of the north rim of French Bay on the southwestern part of the island. The exposure of Grotto Beach Formation is interrupted to the east in Blackwood Bay, an embayment on the northeastern side of French Bay, east of which the interval is probably represented by a facies of eolian origin in the Cockburntown Member and is exposed as far east as the Gulf and Sandy Hook areas along the southern edge of the island (Index map 1).

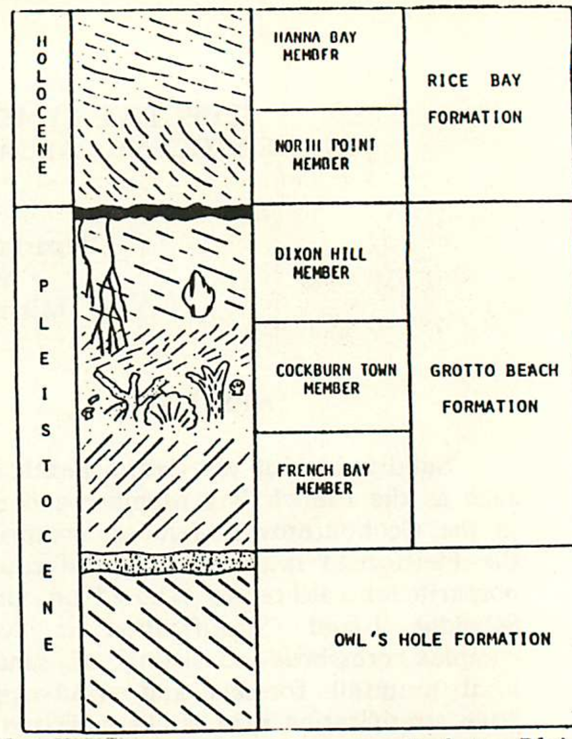


Fig. 1. Nomenclature as applied to Pleistocene and Holocene sedimentary intervals on San Salvador Island (Carew and Mylroie, 1985).

Previous Work

Other sedimentologists have previously noted how grain size and packing within sedimentary units affect the behavior of fluid and subsequent cementation within intergranular pores. Laminations and beds consisting of fine, tightly packed particles have a stronger capability of retaining liquid in the smaller pore spaces because of enhanced fluid surface tension and capillarity (Ward, 1975). The relationship between grain size and fabric, fluid retention, and effective cementation has been observed in marine (Halley and Harris, 1979; Strasser and Davaud, 1986; Evans and Ginsburg, 1987), and eolian (Ward, 1975; McKee and Ward, 1983; White and Curran, 1988) limestones and in unconsolidated quartzose sand of eolian origin (Fryberger and Schenk, 1988). No previous report has further drawn a relationship between eolian processes and grain characteristics and consequent cementation and weathering patterns in eolian limestones, the latter of which may be useful in distinguishing eolian stratification in carbonate rocks.

SEDIMENTARY PETROLOGY

Stratification

The French Bay Member and the eolian beds of the Cockburntown Member of the Grotto Beach Formation form a sequence of complex wedge-and tabular-shaped bedding units consisting of parallel wind-ripple strata and cross strata. These bedding units are internally punctuated by intricate second-order bounding surfaces. Thick cosets of crossbeds and wind-ripple strata are interrupted by a laterally extensive interval of terra rossa calcrete which is up to 15cm thick and forms the present topographic surface in places (Fig. 2). Individual bedding units are preserved as partial or complete dune-form bedding. Complete dune-form bedding consists of topset, brinkset, foreset, and bottomset beds, may compose one entire bedset (Fig. 3), and ranges in thickness from 0.8m to 6.0m. Subhorizontal wind-ripple strata form amalgamated topset beds 0.3m to 1.5m thick and grade downcurrent into gently dipping brinkset laminations which are transitional with sandflow and grainfall foresets (Fig. 3). Angle-of-repose foreset beds are composed of sandflow strata 2-5cm thick and local grainfall laminations 1-3mm thick. Foreset beds ultimately grade downcurrent into bottomset beds which form a complex of sandflow tongues and grainfall and wind-ripple strata.

In modern and ancient eolian quartz sand deposits, climbing translatent strata (Hunter, 1977a,b) or wind-ripple strata are recognized by the thin, even, cyclic occurrence (hence, pin stripe laminations of Fryberger and Schenk, 1988), poorly developed foresets between bounding surfaces, and a general upward-coarsening grain-size trend between lower and upper bounding surfaces (Hunter, 1977a, b; 1981; Fryberger and Schenk, 1981; Schenk, 1983). Wind-ripple strata in rocks are generally so thin that foreset laminations and inverse grading are not clearly discernible. Consequently, the thin, even cyclic nature of the bedding may be the only diagnostic criterion for recognizing wind-ripple strata (Hunter, 1977a; Fryberger and Schenk, 1981).

A wind-ripple stratum in eolian beds of the Grotto Beach Formation is 2 to 5mm thick and was formed by the migration of a wind ripple in an ancient coastal dune setting. Each stratum is cyclic and is composed of an apparent paired or two-fold layering associated with inverse grading and selective cementation of the finer-grained layer. Each layer or lamination is distinguished by color, grain size and packing, and cementation and weathering patterns (Fig. 4). Other criteria suggesting that the thin, even, parallel strata in the Grotto Beach Formation are the product of migrating ripples include the absence of parting lineation, a weathering feature attributed to deposition by upper flow regime plane beds or laminations, and the presence of high index ripple marks on bedding plane surfaces (Fig. 5).

Inverse textural grading is very well developed and is visible in oblique exposures which exaggerate the thickness of each ripple-produced stratum (Fig. 6). The lower portion of each stratum or fine-coarse couplet is characterized by fine grained, moderately well-packed and well cemented sand (next section, Petrography). It weathers to form a white, positive-relief "microledge" on the outcrop. The upper part of each stratum consists of fine medium-grained, moderately to poorly packed, poorly cemented sand laminations (next section, Petrography) which weather to form gray, negative-relief "microrecesses" on the outcrop. Collectively, the white and gray laminations form a sequence of closely spaced, parallel ledges and recesses (Fig. 4).

In general, eolian foreset bedding or crossbedding is made of a series of individual sandflow strata or interbedded sandflow and grainfall strata (Fig. 7). Sandflow strata are lenticular, tongue-shaped units and usually form by grains slipping or avalanching then coming to rest on the steep leeside or slipface of bedforms. Gusts of wind flowing over the crest of a bedform may suspend finer grains which fall out of suspension about midway along and near the base of the leeside to produce grainfall laminations which interfinger with sandflow beds. The bottomset of foreset bedding is usually a complex of grainfall and wind-ripple strata and sandflow toes (Fig. 7). Crossbedding in the Grotto Beach Formation consists mostly of sandflow beds 2 to 5cm thick which are locally interbedded and surrounded by grainfall laminations (Fig. 8). This relationship is poorly preserved in the Grotto Beach limestone and can be locally observed on exposure surfaces which show the up-dip truncations of sandflow and grainfall strata (Fig. 9). The sandflow beds appear as gray, discontinuous lenses enclosed by white grainfall laminations of similar geometry.

Sandflow beds are inversely graded as a result of grain flow sediment mechanics (Bagnold, 1954; Middleton, 1970; Hunter, 1977a,b; 1981; 1985b) so there is a two-fold segregation of grain sizes similar to that in wind-ripple strata. Fine grained sand is concentrated near the base of a sandflow bed, exhibits improved packing, and is well cemented. The fine sand within each stratum grades vertically into medium sand which is loosely packed, and poorly cemented (next section, Petrography). Consequently in outcrop, crossbedding is characterized by a series of white positive relief "micro-ledges" of the basal sandflows and gray, negative relief "micro-recesses" of the upper sandflows spaced 2 to 5cm apart (Fig. 10). The well-cemented ledge-forming laminations can alternatively be identified as grainfall laminations only if: 1. the laminations in question can be traced down-dip into bottomsets and thicken at the expense of sandflow tongues, and 2. the laminations can be seen forming lense-shaped outlines surrounding sandflow lenses. These relationships are only very locally exposed in the French Bay Member and have not been examined in thin section.

Petrography

Details of the grain size and packing and cementation patterns associated with the eolian strata described above can be examined in oriented thin sections. Eleven samples were collected from the French Bay Member of the Grotto Beach Formation; seven oriented samples are from sandflow beds and four oriented samples are from beds of wind-ripple strata. All the limestones examined in this study can be classified as sparsely fossiliferous, peloidal oosparites or ooid grainstones, the allochemical grains of which have been cemented with low-magnesium calcite (Hutto and Carew, 1984) and partly micritized.

The two-fold subdivision of wind-ripple strata as a result of grain segregation during migration of eolian ripples is clearly visible in thin section (Fig. 11). The lower part of each stratum is characterized by fine-grained sand with an average diameter of 0.149mm and the upper layer contains fine medium-grained sand with an average diameter of 0.283mm. Because of smaller grain and pore size and improved packing similar to that observed in basal sandflow beds, the lower layer is well-cemented with equant calcite crystals which completely fill the pore (Fig. 11). Subsequently, this part of the wind-ripple stratum forms a positive-relief, "micro-ledge" weathering pattern on the outcrop (Fig. 4). The upper layer is less well-cemented because of coarser grains of relatively looser packing, larger pores, and therefore poorer fluid retention. These are features similar to those in the upper part of a sandflow bed. Consequently, the upper part of a wind ripple forms a negative-relief, "micro-recess" weathering pattern in outcrop (Fig. 4).

In thin section, sandflow beds are characterized by inverse size grading. A sharp base marks an abrupt grain size change from fine-grained to medium-grained sand between vertically adjacent sandflows. The gradual rather than abrupt change in grain size from fine- to medium-grained sand within each sandflow bed suggests that grain segregation was the result of grainflow mechanics and not from differences between sandflow and grainfall processes. Experimental studies have shown that during a grainflow, finer grains accumulate at or near the base of the flow (Bagnold, 1954; Middleton, 1970; Fryberger and Schenk, 1981). Schenk (1983) has further shown that these finer grains either remain behind on the plane of shearing or are incorporated into the base of the sandflow stratum when the flow ceases.

Fryberger and Schenk (1988) have demonstrated that decelerating gusts of wind can produce normally-graded grainfall strata and that accelerating gusts of wind are capable of producing inversely graded grainfall strata which resemble sandflow strata. However, the inversely graded foreset beds in the Grotto Beach Formation are sandflow beds because of their lenticular nature along strike and because they wedge-out into complex bottomsets of grainfall and wind ripple strata.

The lower portion of a sandflow bed is characterized by medium-grained sand with an average diameter of 0.160mm. The grains exhibit point or tangential to long contacts which suggest moderate to high compaction and packing. Entire intergranular pores are filled with a primary generation of blocky, isopachous calcite cement around each grain and a secondary generation of interlocking calcite cement crystals which filled the remainder of the pore (Fig. 12). This portion of the sandflow bed exhibits a positive-relief, "micro-ledge"-forming weathering pattern in outcrop because of the well-cemented nature of the grains.

Fig. 2. Thin interval of calcrete (arrow) which locally interrupts bedding units in eolian beds of Cockburntown Member, Grotto Beach Formation. Sea-cliff exposure west of the Gulf area. Scale is in inches and centimeters.

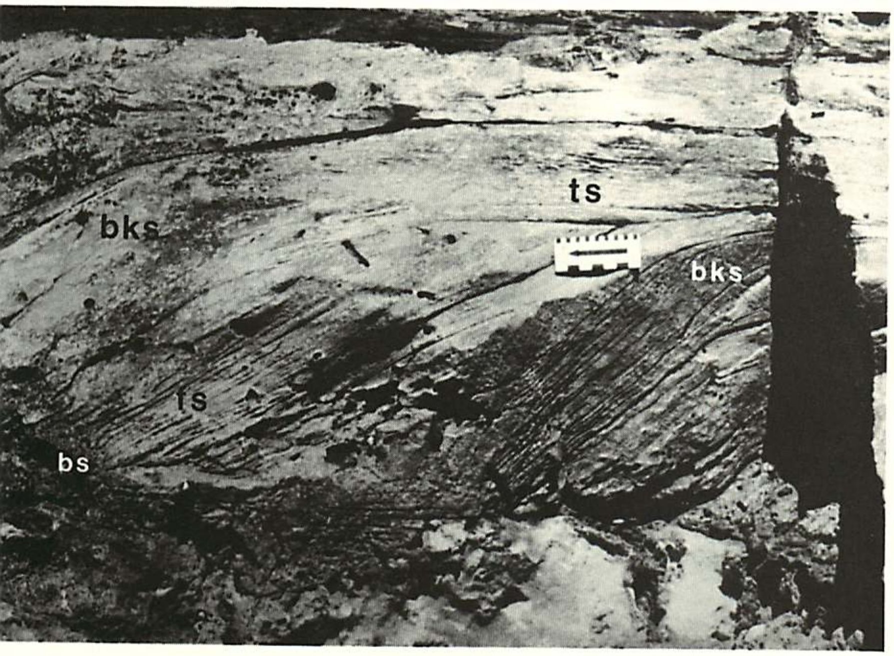
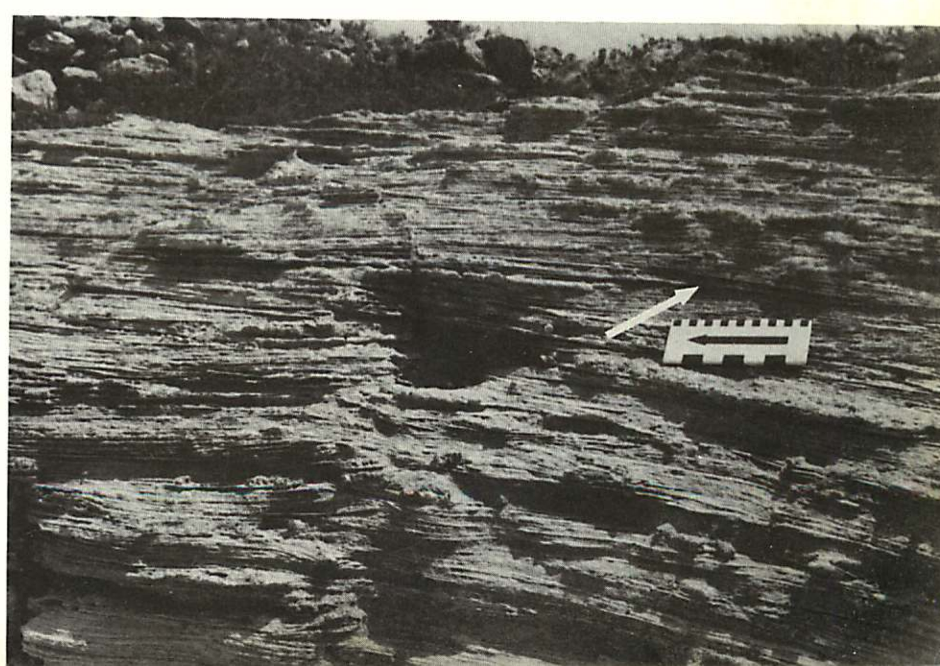


Fig. 3. Crossbed set consisting of topset (ts), brinkset (bks), foreset (fs) and bottomset (bs) beds. Eolian beds of Cockburntown Member, Grotto Beach Formation in seacliffs west of the Gulf area. Scale is in inches and centimeters.

Fig. 4. Wind-ripple strata preserved s amalgamated topset beds. Note local ngular discordances (arrow) between edsets. Scale is in inches and cen-imeters. Eolian beds in Cockburntown ember, Grotto Beach Formation in eacliffs west of the Gulf area.



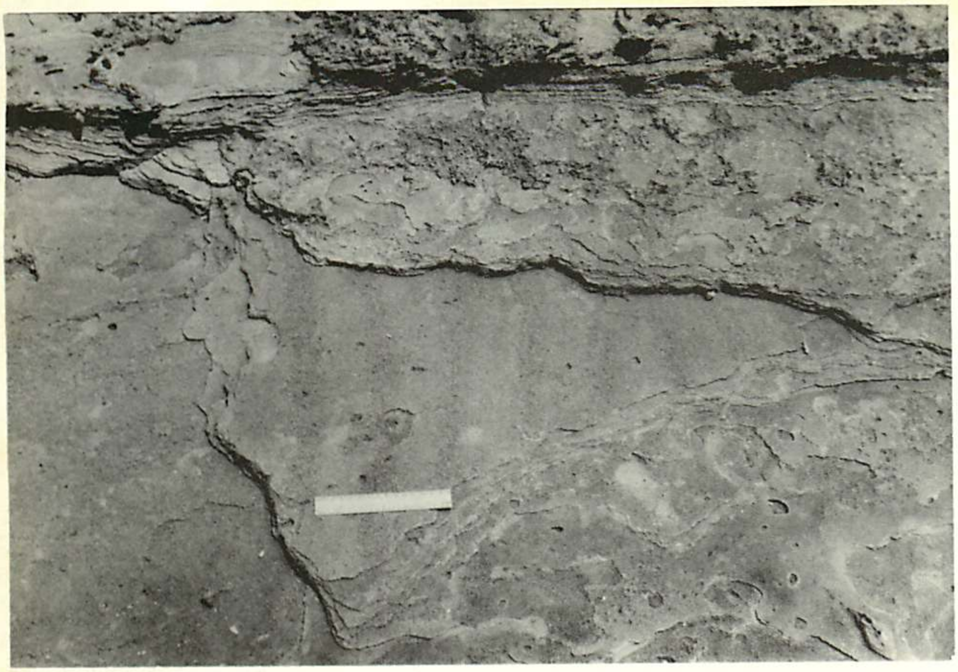


Fig. 5. High-index ripple marks poorly preserved on bedding plane surface within amalgamated wind ripple strata. Scale is 15 cm long. Eolian beds of Cockburntown Member, Grotto Beach Formation in seacliffs west of the Gulf area.

Fig. 6. Thickness of wind ripple strata exaggerated along exposure oblique to bedding. Each stratum is composed of finer-grained laminations in the lower part and coarser grained laminations in the upper part. Dark object in upper left is piece of Sargassum weed. Eolian beds in Cockburntown Member, Grotto Beach Formation in seacliffs west of the Gulf area.

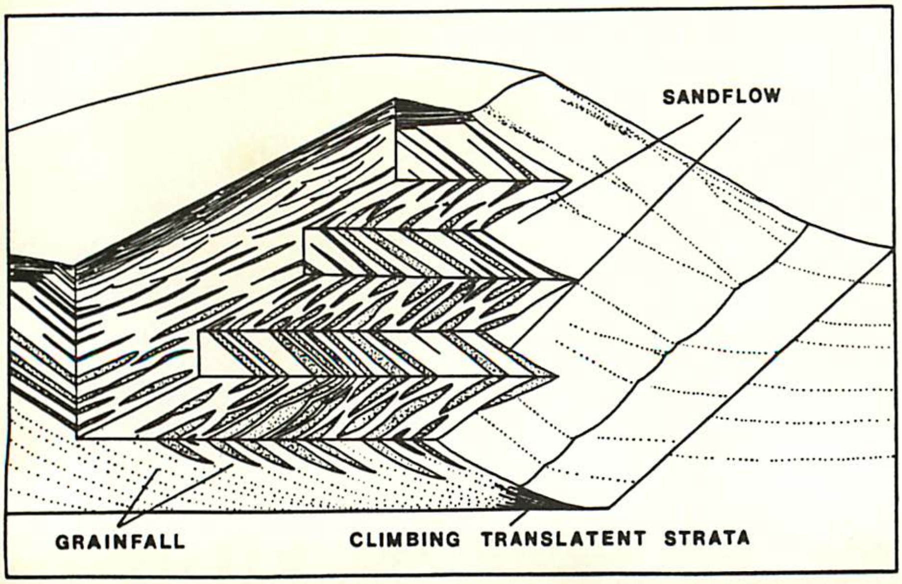


Fig. 7. Geometry and occurrence of stratification types within a general eolian dune-form (redrawn from Hunter, 1977a).

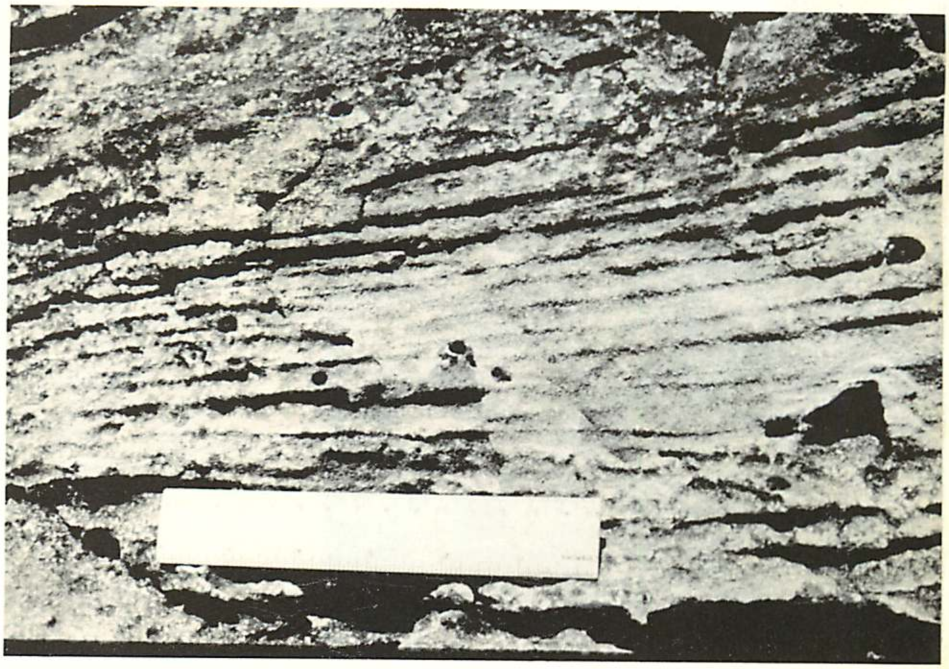


Fig. 8. Tangential bottomset of sandflow beds forming "micro-recesses" and wedging-out into a complex of grainflow and wind ripple strata which form "micro-ledges".

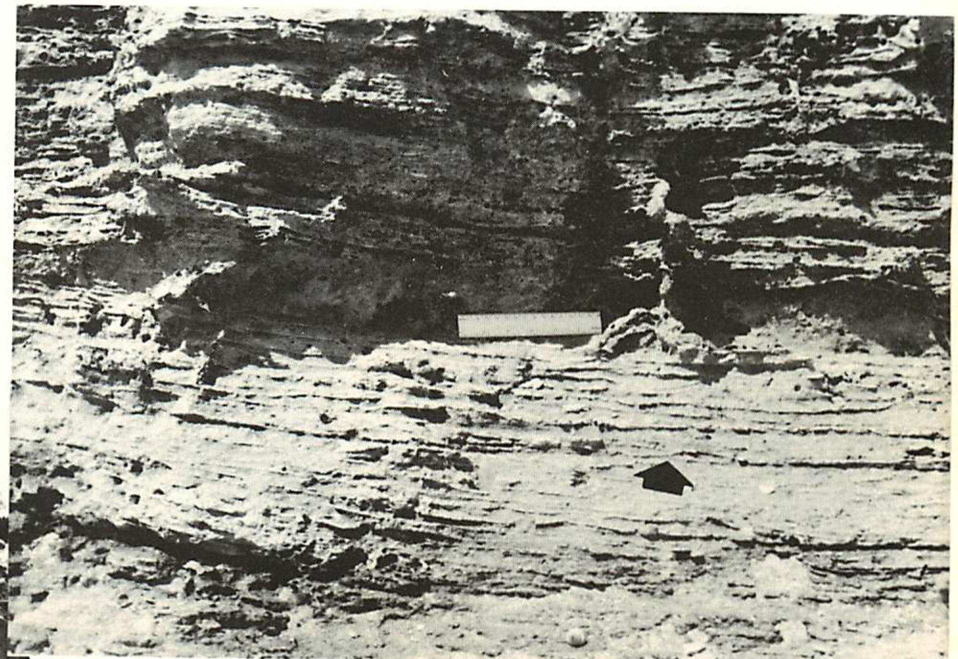


Fig. 9. Locally preserved grainfall laminations (arrow) encircling lenticular sandflow beds in transverse section. Eolian beds in the Cockburntown Member, Grotto Beach Formation in seacliffs west of the Gulf area. Scale is in inches and centimeters.

Fig. 10. Alternating small-scale ledge- and recess-forming strata composed of basal and upper parts of sandflow beds. Eolian beds in the Cockburntown Member, Grotto Beach Formation in seacliffs west of the Gulf area. Scale is in inches and centimeters.

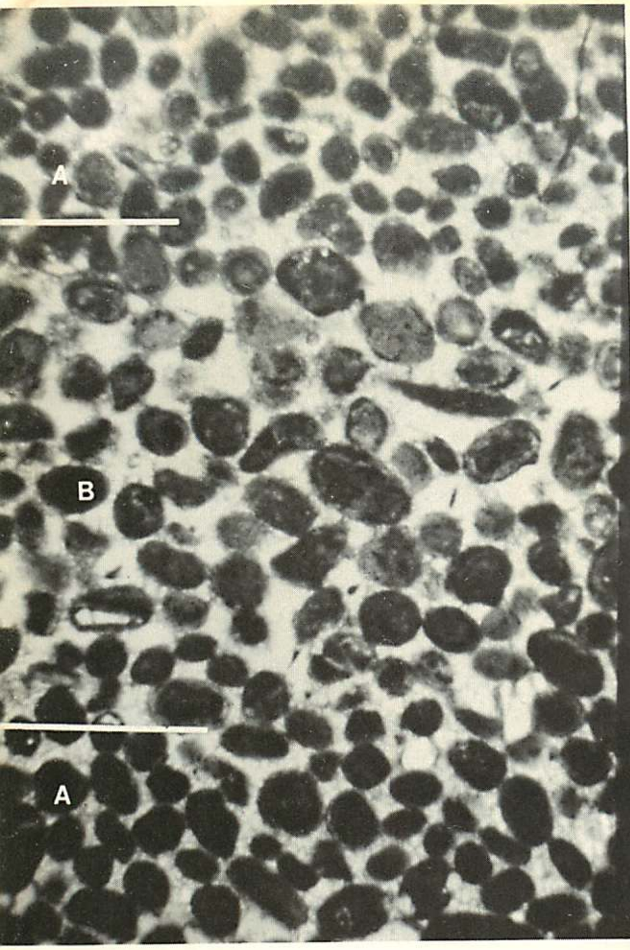


Fig. 11. Photomicrograph of a ripple stratum consisting of basal well-cemented fine grained (A) laminations which grade upward into poorly cemented fine medium grained laminations (B). Low power; uncrossed nicols.

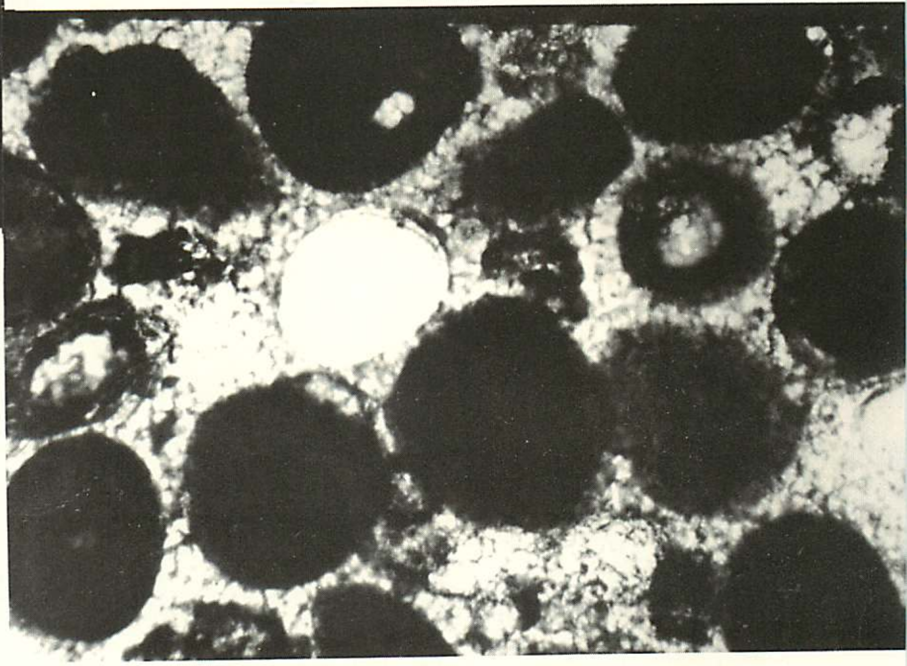


Fig. 12. Photomicrograph of basal part of sandflow bed. Carbonate sand is fine grained and is completely cemented with equant crystals of calcite. Medium power; uncrossed nicols.

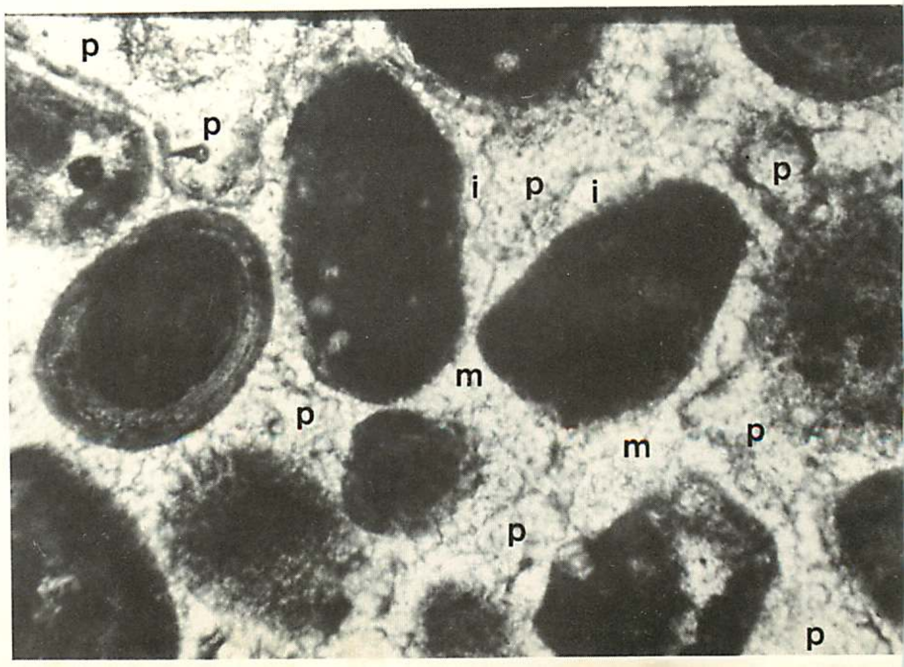


Fig. 13. Photomicrograph of upper part of sandflow bed. Carbonate sand is medium grained and partially cemented with isopachous (i) and meniscus (m) cements. Pore spaces (p). Medium power; uncrossed nicols.

In unconsolidated sedimentary beds, fluid surface tension and capillarity is enhanced by small pore space related to tight grain packing (Bagnold, 1938; Ward, 1975). These conditions create a micro-environment at the scale of a thin bed or lamination which resemble those of a phreatic diagenetic environment where the pore is filled entirely with liquid. Calcite cements formed in freshwater phreatic environments are generally characterized by interlocking equant crystals which fill entire pores (Longman, 1980).

Carbonate particles in the upper parts of sandflow beds are medium-grained sand with an average diameter of 0.330mm. They exhibit point and floating contacts which suggest moderate to low compaction and packing. The grains are held together by equant to bladed isopachous and equant meniscus cement crystals which partly fill the intergranular pores (Fig. 13). Meniscus calcite cements are usually precipitated in a freshwater vadose diagenetic environment where drops of water having meniscus or hour-glass shapes adhere between grains (Longman, 1980). However, the association of meniscus vadose cements with isopachous phreatic cements in the same bedding interval suggests that the pores were temporarily filled with fluid to form isopachous cement and later drained or evacuated by evaporation to form meniscus cement.

CONCLUSIONS AND SUMMARY

Physical subprocesses such as sandflow, grainfall, and the migration of ripples operate in a general wind-blown sedimentary environment to produce sandflow, grainfall, and wind-ripple strata in modern and ancient siliciclastic deposits. These subprocesses have generated similar eolian strata during Pleistocene time in fossiliferous, pelloidal oosparites of the French Bay Member and eolian beds in the Cockburntown Member of the Grotto Beach Formation exposed on southern San Salvador Island, Bahamas. Interpretations in this study suggest that grain textures inherited from eolian subprocesses have influenced cementation patterns among different eolian strata. Cementation patterns are expressed as ledge- and recess-forming strata in outcrop. The relationship between cementation-weathering patterns may be useful in distinguishing fine structure in eolian calcarenites.

Ripples associated with ancient eolian dunes have produced wind-ripple strata in the Grotto Beach Formation. Each stratum is composed of a lower fine sand lamination and an upper fine medium sand lamination. Differences in weathering pattern reflect cementation patterns which are controlled by grain texture. Smaller pores are related to finer grain size and tighter grain packing and favor strong fluid capillarity and retention. Consequently, laminations which have such a texture are well cemented and crop out as "micro-ledges" in weathered exposures. Conversely, larger pores are related to coarser grains and looser packing which diminish fluid retention and capillarity. Incomplete cementation of pores by meniscus calcite cement has resulted in calcarenite laminations which form "micro-recesses" in weathered exposures.

Grain flow mechanisms have controlled the geometry and distribution of sand flow beds and internal characteristics such as grain size and packing which ultimately have controlled cementation patterns in each bed. Grain segregation during grain flow produced a concentration of more tightly packed, fine-grained sand at the base and a gradual vertical change toward more loosely packed medium-grained sand in the upper part of sandflow beds. Fluid surface tension and capillarity was enhanced by small pore space related to fine grain size and greater grain compaction in the basal sandflow. Therefore, at the time of cementation, interlocking, bladed, equant crystals of low-Mg calcite, as isopachous rim and complete pore-filling cement, precipitated in the intergranular pore space. The pattern of complete cementation in the basal sandflow is expressed in outcrop as a thin positive-relief "micro-ledge". Conversely, medium-grained sand in the upper parts of sandflow beds exhibits looser packing resulting in larger pores which have been partially cemented with equant isopachous and meniscus calcite cement. This part of the sandflow is recognized as a "micro-recess" between well cemented "micro-ledges" in weathered outcrops.

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