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Effects of Sea Spray on Vadose Diagenesis of Late Quaternary Aeolianites, Bermuda

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ABSTRACT

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This paper examines the role that sea spray plays in the diagenetic alteration, cementation and weathering of late Pleistocene aeolianites in the vadose zone from Bermuda. Aeolianites (dune sands cemented by calcium carbonate) from three distinct stratigraphic units, the Southampton Formation, the Rocky Bay Formation and the Belmont Formation, which equate with Oxygen Isotope Stages 5a, 5e and 7 respectively, have been sampled from sections in the spray zone and in the absence of any significant sea spray input in fresh, recently excavated exposures, inland.

Techniques employed to analyse the rock samples include microscope studies of thin sections, scanning electron microscope (with EDX), inductively coupled plasma spectrometry and ion chromatography. The findings of this research indicate that processes operating in the spray zone result in accelerated rates of diagenesis, probably as a result of mixing corrosion causing dissolution of the contained allochems, which then act as the main source for the low Mg-calcite cement. Additional sources of $CaCO_3$ for the cements come from Ca cations in the sea spray; terrigenous aerosols both from within the sea spray and in the atmosphere; and possibly from dissolution of overlying carbonate deposits.

Compared to the normal rates of vadose diagenesis out of the influence of sea spray, more rapid rates of diagenesis in the spray zone have resulted in elevated levels of total cements, increased secondary porosity, lower primary porosity values and fewer preserved allochems in the sediments in the spray zone.

Halite is present in the crystalline state within the aeolianite but it does not appear to be important in weathering; it merely coats grains and cements, and partially infills pore spaces. This may be because the individual pore spaces within the aeolianites are relatively too big for the halite crystals to exert any stresses on the surrounding clasts and cements.

ADDITIONAL INDEX WORDS: *Carbonate diagenesis, cemented dune sands.*

INTRODUCTION

The vadose zone is known to be an extremely complex diagenetic environment (GARDNER and MCLAREN 1994), especially at or near coasts. This is because sea spray is thought to affect and accelerate the processes of diagenesis. Many studies of vadose diagenesis in Pleistocene sediments have been conducted in coastal environments and have concentrated on coastal dunes and raised beach deposits. Along coasts, sea spray is thought to supply significant quantities of ions to the vadose diagenetic environment and these ions may be important in sediment alteration, cementation and weathering. The addition of spray into dune sands aiding cementation (predominantly by low-Mg calcite) in the meteoric vadose zone is of specific interest here and it is a different environment from that in which beachrocks form. Beachrock develops in the intertidal (vadose marine) zone, where cementation (which is normally fibrous aragonite) commonly occurs between low and high tide levels (See SCOFFIN, 1987 for further details on beachrocks). Beachrocks are not given any further consideration in this study.

Sea spray droplets of various sizes are ejected into the atmosphere when trapped air bubbles rise to the surface of the sea and break (BROWN *et al.,* 1995). According to CHESSELET *et al.,* (1972), sea spray comprises terrigenous dust particles, water with similar ionic ratios to sea water and ionic fractionated marine aerosols. In terms of deposition of marine aerosols, there are large droplets, which have a short residence time in the atmosphere and are deposited close to the shore (GUSTAFSSON and FRANZEN, 1996), as well as microscopic droplets, which have a long residence time in the air and can be transported several kilometres inland (FRANZEN, 1990).

Salt weathering in the marine zone has been well documented (*e.g.* WELLMAN and WILSON, 1965; MOTTERSHEAD, 1989; MOTTERSHEAD and PYE, 1994). "In coastal situations spray derived from the ocean can cause the accumulation of substantial amounts of salts which can then cause aggressive weathering" (GOUDIE and VILES, 1997, p65). But does the deposition of sea spray into sediments just cause weathering or can it also aid in case hardening and cementation in the vadose zone under certain conditions? To date, very little is known about the balance between the weathering and diagenetic effects of sea spray.

The precipitation of cement is controlled by five main fac-

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tors: presence of supersaturated solutions; degree of supersaturation of the pore fluids; solution composition; rate of pore water movement; and chemistry of the substrate. Carbonate-bearing solutions can become supersaturated by a number of means including: a loss of CO_2; an increase in temperature; evapotranspiration; a decrease in salinity, for example by mixing of high and low salinity solutions (LAND *et al.*, 1967); or an increase in salt concentration such as by evaporation. The latter two processes in particular are of relevance to vadose diagenesis in the spray zone.

Many researchers have suggested that sea spray is an important source of calcium carbonate for cement (*e.g.* HARRISON, 1977; JONES and KAHLE, 1986). MCNAMARA and USSELMAN (1972), studying soils in Antarctica, found crystals of calcite, gypsum, aragonite and halite, which they proposed were marine in origin. FRIEDMAN (1964) and JAMES (1972) have shown that sea spray at Pleistocene cliffs may account for the high-Mg contents in rocks and cements, which they suggest indicates a marine influence. JAMES *et al.* (1986) found high concentrations of Ca Mg, Na and K in rain falling on the Ainsdale sand dunes in Merseyside, England, which could act as a potential source of calcium for cement.

MCLAREN (1995) conducted the first attempt at a systematic analysis of the effects of sea spray on vadose diagenesis, and the results showed that, on a local scale, sea spray can be of fundamental importance in the fresh-water diagenesis of late Pleistocene dunes and raised beaches. Working in Jamaica, The Bahamas and Mallorca, she found that coastal deposits exposed to differing amounts of sea spray also showed varying amounts of diagenetic alteration. Deposits exposed to greater amounts of sea spray had more secondary porosity as a result of greater amounts of dissolution of the contained allochems and the deposits also tended to be better cemented. However, this earlier study was conducted on a relatively local scale, only extending inland from the coast to a maximum of 500 metres and most of the deposits (81%) were less than 15 metres from the shoreline. All but one of the outcrops were exposed to some amount of sea spray.

The aims of this research are to gain a fuller understanding of the effects of sea spray by comparing deposits of the same age in sections exposed to sea spray at the coastline with sections inland that have been only recently exposed (current quarrying) and so have not been exposed to significant sea spray. In addition, aeolianites of three different ages are studied to see if there are any changes in the processes or patterns of diagenesis with time.

Although late Pleistocene aeolianites are well preserved (for example in the Caribbean, the Middle East, South Africa and Australia), there are very few sites where the same lithological and stratigraphical units of an aeolianite can be found both inland in fresh exposures as well as at the coast in the spray zone. Bermuda contains many good exposures of thoroughly mapped and extensively studied aeolianite (VACHER *et al.*, 1989; HEARTY and VACHER, 1994; VACHER *et al.*, 1995; and VACHER and ROWE, 1997) of various ages (that have been well dated) both at the coast and inland. Here it is possible to carry out research on vadose diagenesis in dunes of the same age, lithology, and that have comparable histories of climatic conditions. All of these factors combine to make Bermuda a highly suitable location to carry out this type of research.

FIELD LOCATIONS

Bermuda (32° 20′N 64° 45′W) comprises 360 small limestone islands situated about 920 km east of the coast of North Carolina (U.S.A). It has a total surface area of 54.5 km^2 and 103 km of coastline. The climate in Bermuda is subtropical and influenced by the Gulf Stream, which results in mild winters (mean about 17°C) and warm humid summers (average about 27°C) and has a mean annual rainfall of 1,475 mm. Ocean winds are often moderated by the warm Gulf Stream with strong winds common in winter and hurricanes occurring between June and November.

The islands consist of units of wind blown dune sands and beach deposits which are thought to represent sediment accumulation during interglacial highstands in sea level. Weathering of the limestones and soil formation occurred during minor breaks within and between interglacial substages (VACHER *et al.*, 1995). These changing environmental conditions have resulted in a series of intercalated carbonate deposits and red palaeosols. An extensive review of Bermuda's Quaternary geology has recently been carried out by VACHER *et al.* (1995) and VACHER and ROWE (1997).

Determining the chronostratigraphy of the islands has been based on four main techniques: lithostratigraphy (*e.g.* VACHER 1973, LAND *et al.*, 1967); uranium series dating (*e.g.* HARMON *et al.*, 1983); aminostratigraphy (*e.g.* HARMON *et al.*, 1983; HEARTY *et al.*, 1992); and electron spin resonance dating (HEARTY and VACHER, 1994). The combination of the different dating techniques provides what appears to be a relatively reliable chronosequence, and HEARTY and VACHER (1994) have proposed a sequence of evolution of the islands of Bermuda from approximately one million years ago to present day.

According to HARMON *et al.* (1983), only twice in the past 250,000 years has sea level in Bermuda been above present: at 200,000 years ago when sea level was +2 metres and at 125,000 ±4 ka (Oxygen Isotope stage 5e) when sea levels were +5 (±1) metres above current sea levels. However, VACHER and HEARTY (1989) have argued that sea levels were also close to present day near the end of Oxygen Isotope Stage 5a. Deposits of Oxygen Isotope Stage 5 age have therefore only been exposed to vadose conditions during their history and those of Oxygen Isotope stage 7 will have been exposed to marine or phreatic conditions only if they are below 5 metres above present sea level and then only for a relatively short period (a few thousand years) (HARMON *et al.*, 1983). According to MORSE and MACKENZIE (1990) "in 125,000 years little has happened to the bulk of the Bermudian limestones above present day sea level because they have had little contact with phreatic zone waters"(p337).

For the purposes of this study three ages of aeolianite were selected: (1) the Southampton Formation (Oxygen Isotope stage 5a); (2) the Rocky Bay Formation (Oxygen Isotope stage 5e); and (3) the Belmont Formation (Oxygen Isotope stage 7). The locations and stratigraphic identifications of the sites studied here agree with the published geologic map of VACH-

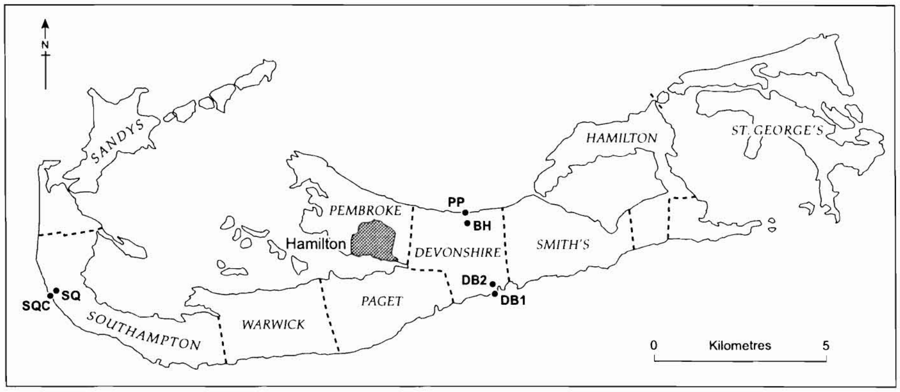

Figure 1. Map of Bermuda showing the locations of the sections studied.

ER *et al.* (1989). Twenty rock samples were collected from each site giving a sample total of 120. Samples of the same age are compared to try and identify any variability in diagenetic processes and products within individual formations that are exposed to different amounts of sea spray. Also the three, differently aged, formations were selected to see if any patterns could be picked up in terms of changes in diagenetic products with the age of the deposits.

The outcrops of the Southampton Formation selected for study were found at the end of Lukes Pond Lane on the west coast of Bermuda in Southampton Parish (Figure 1). Here there is an active quarry (SQ), where the aeolianite is being extracted for sand. A clean section, which had only recently been exposed, was chosen for sampling (Plate 1). The second site sampled (SQC) was due west from the quarry at the coastline (Figure 1). The section selected was at the back of a modern beach in a cliff exposure. Two sites were selected for analysis in the Rocky Bay Formation on the north coast of Bermuda in Devonshire Parish. The section inland was just off Barkers Hill (BH) to the east of the road at the edge of the Ocean View Golf Course. Here there was a small new quarry exposing the Rocky Bay aeolianite (Plate 2). The location chosen in the spray zone was in aeolianite outcropping on the coast at Palmetto Park (PP). The final area was in the Belmont Formation exposed in Devonshire Parish at Devonshire Bay (Figure 1). The inland exposure was along Devonshire Bay Road (DB2) on a relatively fresh clean cutting and the outcrop in the spray zone was at the coast in a cliff outcrop close to sea level (DB1) (Plate 3). None of the sites sampled contained any palaeoerosion surfaces or palaeosols within the aeolianite units.

LABORATORY WORK

The research methods employed primarily involved the design of a sampling strategy followed by the collection of samples in the field. Analysis of thin sections using a petrographic microscope formed the basis of this research. Samples were impregnated with araldite epoxy resin under vacuum before thin sectioning. The types and percentages of particles, the primary porosity and the diagenetic changes were all studied in detail using a point counter (Swift Model F). The thin sections were stained with Alizarin red S, Fiegl's solution and Titan yellow to distinguish between low-Mg calcite, aragonite and high-Mg calcite respectively. The sample target was 550 points for all samples, and this allowed the determination of the percentage of the various constituents present in the rock, calculated as a percentage of the total bulk rock volume.

Forty subsamples of the rocks collected were examined in detail under the scanning electron microscope (SEM) (Hitachi S-2500). The broken faces of the rock chips were coated in a mix of gold and palladium. The mineralogy and chemistry of individual grains and crystals were also analysed *in situ* under the SEM using an Energy Dispersive X-ray Analyser (EDX).

Inductively Coupled Plasma Spectrometry (ICP) was used to measure the concentrations of the various elements present. The sediment was crushed and 0.2 grams was dissolved in 2 mls of concentrated HCl. The solution was then made up to 20 mls with distilled water and then run through the ICP. ICP analysis was conducted to determine the concentrations of Al, Ca, Fe, Mg, Mn, Na, and Sr present in the samples, which then allowed a comparison of those sampled in the spray zone with those inland. Chloride was measured by ion chromatography. Rock powder (10–20 grams) was leached with a known volume of distilled deionised water for 24 hours before analysis of the extract.

Whole rock samples were analysed in the ICP to compare the deposits from the same rock formation that are in the spray zone with those not exposed to sea spray. This allowed a comparison of the amounts of Ca, Sr and Mg in the clasts and cements as well as any elements that are present in solution in the pore spaces that have not crystallised out.

RESULTS

Mineralogical studies

The aeolianites are made up of carbonate material largely consisting of biogenic fragments. The Southampton and Belmont Formations studied are made up predominantly of skeletal fragments (a mix of coral, molluscs, foraminifera, algae

Plate 1 Section sampled inland in the Southampton Formation (SQ)

and echinoids) sourced mostly from reef zones from the south and west of Bermuda. The Rocky Bay aeolianite studied comprises largely lagoonal organisms blown inland from the north of the island. All the cements studied are low Mg-calcite and display vadose characteristics (see McLaren, 1993).

Southampton Formation Samples (Isotope Stage 5a)

Table 1 shows the means and standard deviations of the percentages of unaltered allochems, total cement, primary porosity and secondary porosity of all the samples studied. It can be seen that the samples from the Southampton Formation (SQ and SQC) collected from the spray zone contain on average 12.1% more total cement, 3% more secondary porosity and 16.2% less primary porosity than the deposits from inland. Both sites contain similar amounts of unaltered allochems, which indicates that localised dissolution of allochems and reprecipitation as cement does not appear to account for the additional cement in the spray zone compared to inland. However, it is unknown what the initial content of unaltered allochems was in the sand dunes. In addition, it is not known whether sediments originally overlying the outcrops have been dissolved out and have acted as a source for cement. Table 2 shows the student t-test values for SQ and SQC. The values for total cement, primary porosity and secondary porosity are all well above the 0.01 significance level. This indicates that there is a significant difference between the samples at the coast and those inland in terms of both types of porosity and cement values indicating that different diagenetic processes or rates of processes are operating in the two locations.

Rocky Bay Formation Samples (Oxygen Isotope Stage 5e)

Table 1 shows that the outcrop in the spray zone (PP) is better cemented than the outcrop in the new quarry (BH), but only by 6.4% on average, and has 5.3% more secondary porosity, lower primary porosity (14.5% less on average) and allochem contents (5.1% lower on average). Plate 4 shows only the minor development of rim and meniscus cements in the Barkers Hill aeolianite. Student t-tests were calculated to test for the statistical significance of the sea spray exposure data (Table 3). For the total cement value the apparent differences revealed by the sample means could be accounted for by chance in the sampling process. The primary and secondary porosity values, however, suggest that the null hypothesis can be rejected as the t values are well above the critical value of 2.7. Of the three sites studied in the spray

Plate 2 Section sampled inland in the Rocky Bay Formation (BH)

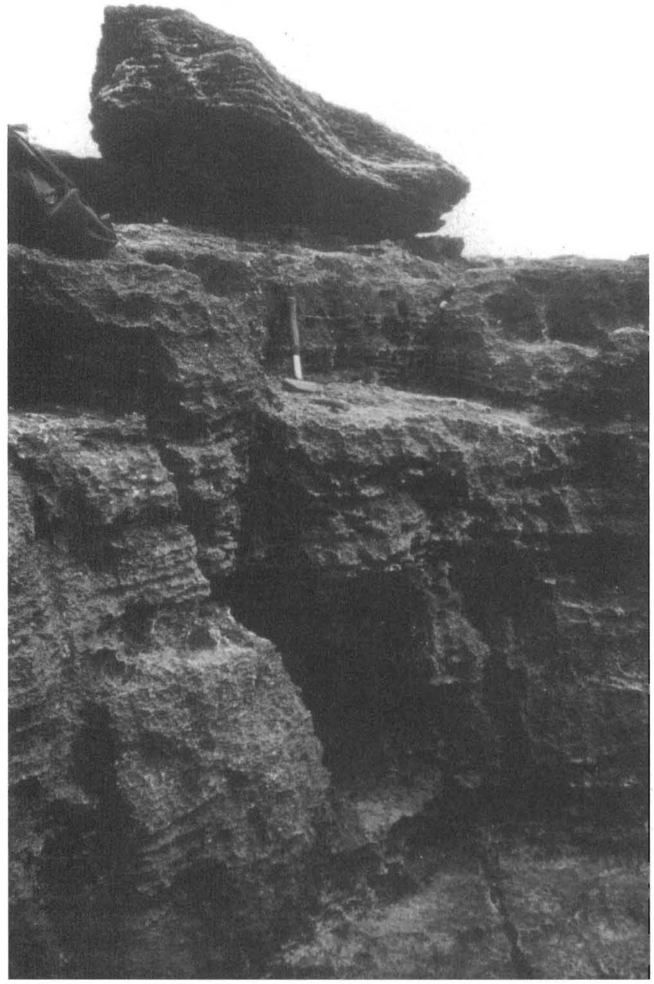

Plate 3 Section sampled at the coast in the Belmont Formation (DB1)

zone, the Palmetto Park area is in the least-exposed location and probably receives less incoming sea spray.

Belmont Formation Samples (Oxygen Isotope Stage 7)

From Table 1 it can be seen that on average the deposits exposed to sea spray (DB1) contain 13.3% more total cement, 4.2% more secondary porosity, 4.6% less primary porosity and 13.4% fewer allochems than the section sampled inland (DB2). Plate 5 is an SEM image showing well-developed rim and pore-filling cement in a sample from the Belmont Formation in the spray zone.

Looking at the student t-test values (Table 4), the total cement and secondary porosity means of the two deposits are statistically significant at the 0.01 critical value and primary porosity is statistically significant at the 0.05 significance level. The mean values of total cement, primary porosity and secondary porosity in the two outcrops from the Belmont For-

Table 1. *Summary of the point counting analyses on all the samples studied.*

Section	Sample size	Allochems mean %	σ	Total cement %	σ	Primary porosity %	σ	Secondary porosity %	σ
SQC	20	57.2	3.4	24.1	2.0	14.9	2.7	3.3	0.9
SQ	20	55.7	5.3	12.0	3.8	31.1	5.4	0.4	0.3
PP	20	51.8	4.8	23.4	3.6	10.4	0.8	5.6	1.5
BH	20	56.9	2.1	17.6	2.7	24.9	2.5	0.3	0.3
DB1	20	49.3	3.2	32.9	4.8	12.1	4.0	4.9	1.7
DB2	20	62.7	4.8	19.6	3.5	16.7	7.4	0.7	0.9

Table 2. *Student's t values for SQC and SQ from the Southampton Formation.*

SQC V SQ	t	Critical value (0.01) 1 tailed test
Total cement	8.8	2.7
Primary porosity	8.5	2.7
Secondary porosity	9.8	2.7

Table 3. *Student's t values for PP and BH from the Rocky Bay Formation.*

PP V BH	t	Critical value (0.01) 1 tailed test
Total cement	0.82	2.7
Primary porosity	17.6	2.7
Secondary porosity	10.8	2.7

mation are significantly different, resulting in elevated levels of diagenetic alteration in the spray zone compared to inland.

If, looking at the effects of time, age is the only variable considered, and not location, then the range of diagenetic variability appears to be large. For example, the range in total cement for the Southampton Formation is between 6.2% and 27.9%, for the Rocky Bay Formation is 14.2–36.1%, and for the Belmont Formation is 13–39.4%. Such ranges in the amounts of total cements from deposits of the same age indicate that there are varying rates of diagenesis occurring. But, looking at variations between the deposits of various ages that are either in the spray zone or are not, it can be seen that there is an increase in the amount of cement from the youngest deposit (SQ—with a mean of 12%, σ3.8) through BH (with a mean of 17.6%, σ2.7) to the oldest (DB2—with a mean of 19.6%, σ3.5) all inland, and also in the spray zone from the youngest (SQC—with a mean of 24.1%, σ2) through PP (with a mean of 23.4%, σ3.6) to the oldest (DB1—with a mean of 32.9%, σ4.8). There is also a general trend of increasing secondary porosity and decreasing primary porosity with age. Therefore, it is important to study deposits from the two different environments separately as the rates of diagenesis vary. Enhanced and accelerated diagenesis has occurred in the spray zone compared to inland where the deposits studied have only been recently exposed.

Thus it can be seen that there is a significant difference in the degree of diagenetic alteration in deposits in the spray zone compared to those not exposed to sea spray. But can the effects of the input of ion-rich sea spray be detected in terms of any changes in the geochemistry of the aeolianites? The next step is to look at the differences in the geochemistry of

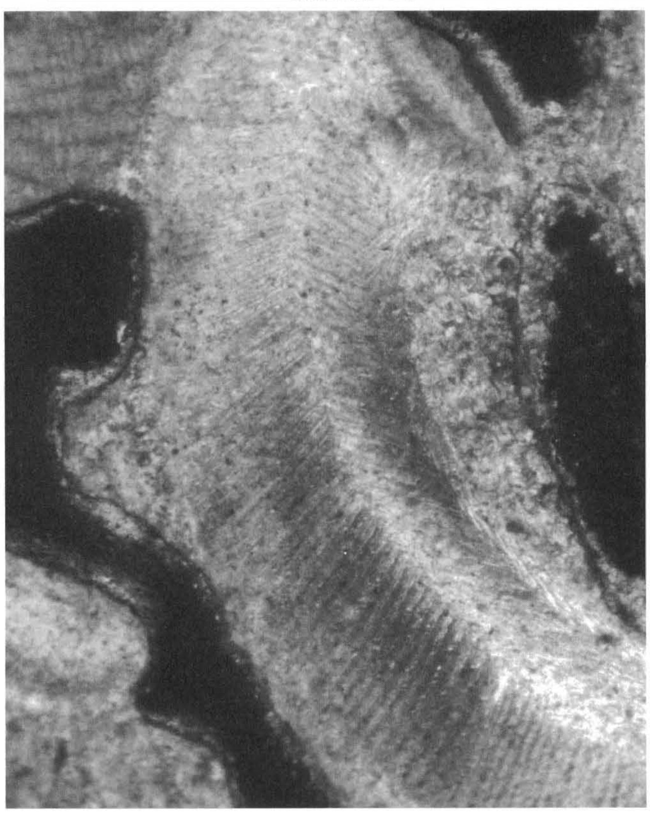

Plate 4 Thin section (crossed nichols) showing a poorly lithified bioclastic aeolianite with incipient rim and meniscus cement types, from sample BH4 sampled inland.

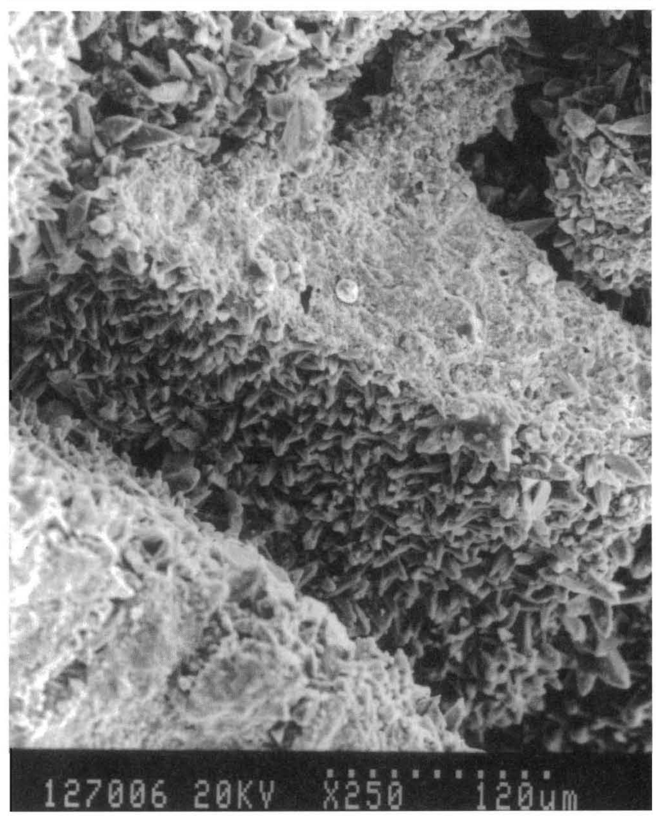

Plate 5 SEM image showing well-developed dog-tooth spar in the form of rim and pore-filling cement types, from SQC1 in the sea spray zone.

Table 4 *Student's t values for DB1 and DB2 from the Belmont Formation.*

DB1 V DB2	t	Critical value 1 tailed test
Total cement	5.6	2.7 (0.01)
Primary porosity	2.22	2.02 (0.05)
Secondary porosity	6.9	2.7 (0.01)

the two environments to see what is happening to the sea spray ions once they have infiltrated into the dune sediments.

Geochemical analyses

Figure 2 shows the values for calcium for the three sections inland and the three sections in the spray zone. For the samples inland, the calcium levels are fairly constant showing a very slight increase with age from SQ (235011 ppm) to DB2 (268153 ppm). The samples in the spray zone contain more calcium than those inland and also show a distinct increase in the amount of calcium up the section profile from the base towards the top. This is expected as more cement is present in the deposits in the spray zone as is evident in Table 1. There also appears to be a near surface effect resulting in increased cementation towards the top of the sections. This surface induration is probably as a result of higher levels of evaporation close to the top, concentrating various ions and aiding the precipitation of carbonate cements.

For all the samples, magnesium levels are quite variable in the deposits of different ages (Figure 3). In general, the samples from the Rocky Bay Formation contain the lowest magnesium levels. This is probably because the Barkers Hill aeolianite contains more lagoonal species, which are dominantly aragonitic (VACHER, 1973) in comparison to the other aeolianites studied, which contain more high-Mg calcite reef-suite species. Samples from the spray zone tend to contain less magnesium than those sheltered from the spray with the exception of Palmetto Park, which contains a slightly higher relative proportion of foraminifera (high-Mg calcite) in two of the samples, than the samples studied at Barkers Hill. Lower magnesium contents in the deposits exposed to the spray zone may be a result of preferential dissolution of high-Mg calcite allochems by mixing corrosion.

Consistent with the pattern described above, the Rocky Bay Formation generally contains more strontium than the other deposits (Figure 4). Strontium concentrations for the Southampton Formation and the Belmont Formation show quite similar patterns although the older unit contains slightly less Sr. VOLLBRECHT and MEISCHNER (1996) recorded similar strontium contents in coastal carbonates from Bermuda.

Sodium (Figure 5) and chloride (Figure 6) display similar patterns. There is consistently and significantly more of these elements in the deposits exposed to sea spray, especially at SQC (Southampton Formation) with mean Na concentrations of 14492 ppm and Cl concentrations of 25356 ppm. This is in comparison to the mean values of 1258 ppm for Na and 1941 ppm for Cl inland at SQ. The samples in the spray zone also show a general increase in concentration up towards the top of the profiles. So, as well as receiving spray from the outcrop face at the side, it appears that spray landing on top of the deposits infiltrates down into the aeolianites. Evaporation then concentrates these elements near to the surface. Because Na and Cl are relatively major ions in sea water and minor in meteoric waters this strongly indicates a marine source for these ions.

Aluminium patterns are interestingly very similar to those of the calcium (Figure 7). With all samples, there is an increase with age, and there are generally higher levels in the spray zone than inland. In addition, there is an increase with height towards the top of the profiles in samples from the spray zone. As there is little Al in sea water its presence may indicate a terrigenous source, possibly as part of the aerosols making up the sea spray.

Fe (Figure 8) and Mn (Figure 9) levels are generally low in all samples but display similar general patterns with slight increases with age and higher concentrations in the samples in the spray zone compared to those inland. It is likely that the source for both these elements is similar to that of the aluminium, from terrigenous dust particles. In vadose cements, Fe and Mn are often absent this is because the vadose zone is usually an oxidising environment and "the oxidised states of these elements can not be incorporated in the calcite lattice" (MOORE, 1989 p180). Enrichment of these elements is likely to be from windborn material much of which origi-

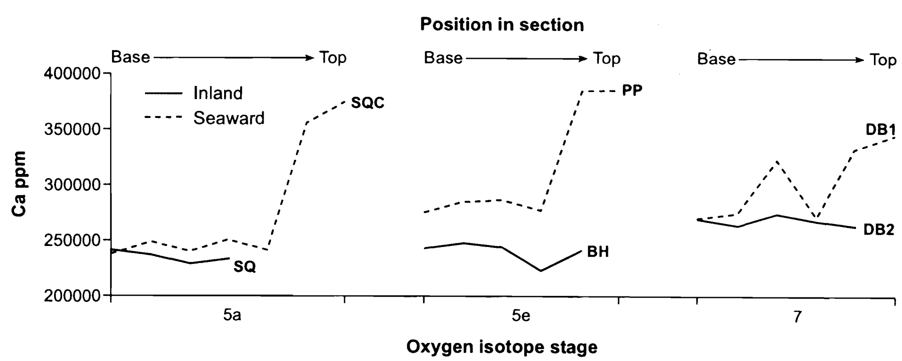

Figure 2. Plot showing the concentrations of Ca in ppm for the all the deposits studied in the sea spray zone and inland.

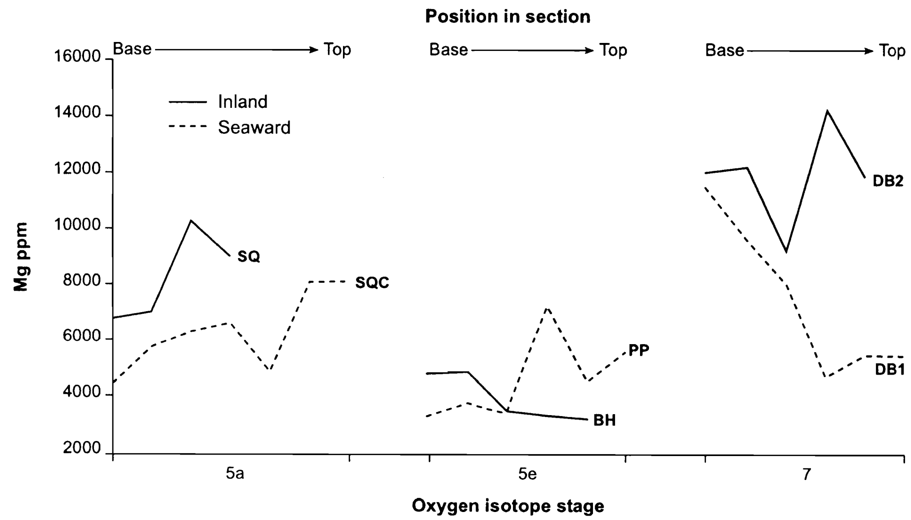

Figure 3. Plot showing the concentrations of Mg in ppm for the all the deposits studied in the sea spray zone and inland.

nates in the Sahara desert and is transported across the Atlantic (HERWITZ. *et al.*, 1996). CHESTER *et al.* (1971) have measured the summer dust loadings in the air in Bermuda and they average 6 μgm^{-3} of air, which could easily be incorporated into the aeolianites through wet or dry deposition and infiltration. VOLLBRECHT and MEISCHNER (1996) also analysed the geochemistry of carbonates in Bermuda and found that the Fe and Mn contents were insignificant but no figures were given.

An analysis of the relationships between ions may help to indicate some of the processes operating. Pearson's product moment correlation was calculated for all the samples to investigate any correlations between elements. Good correlations were found between Na and Cl (0.99), Na and Ca (0.65), Na and Al (0.6), Ca and Al (0.96), Ca and Mn (0.73) and Al and Mn (0.85). It appears from these statistics that:

(a) the close positive correlation suggests that Na and Cl are present in the form of sodium chloride;

(b) those samples with more halite present also tend to contain more Ca, probably in the form of cements as is indicated in Table 1;

(c) where there is more Ca present (in the form of cement) there tends to be more of the terrigenous Al and Mn cations. There tends to be an increase in all these elements towards the top of the outcrops where aerosols can infiltrate and evaporation can increase the concentration of ions. The terrigenous elements may be accumulating as part of the very initial stages of soil development.

SEM/EDX Analyses

The presence of many crystals covering the low Mg-calcite vadose cements is evident on studying the samples under the

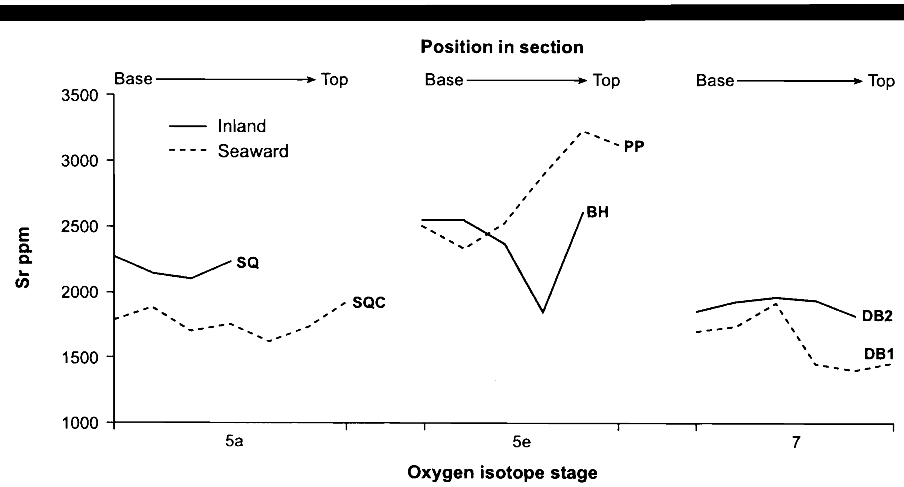

Figure 4. Plot showing the concentrations of Sr in ppm for the all the deposits studied in the sea spray zone and inland.

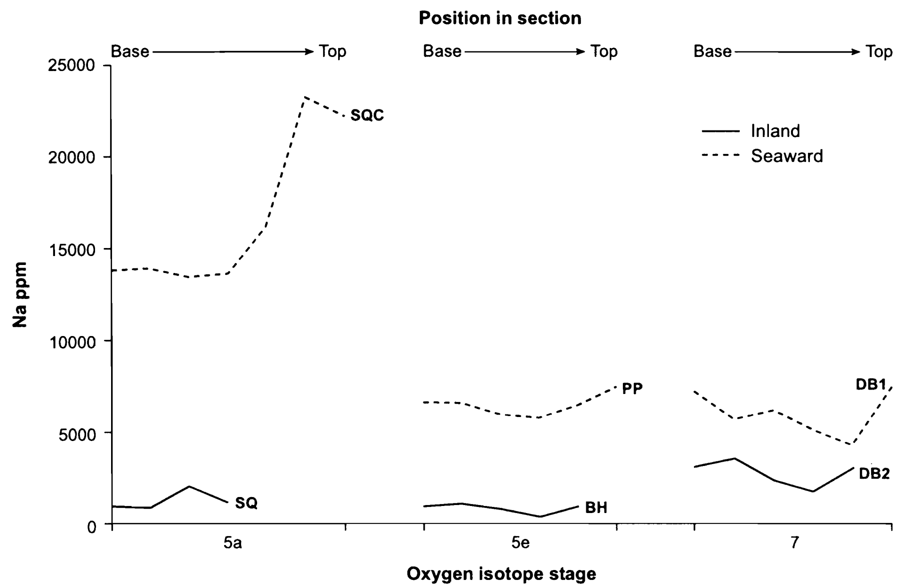

Figure 5. Plot showing the concentrations of Na in ppm for the all the deposits studied in the sea spray zone and inland.

SEM. This mineral is found: as grain coatings; overlying cements; partially filling pores spaces; and in the form of meniscus cement (Plates 6 and 7). The EDX showed that these crystals are sodium chloride (Figure 10), and they appear to have formed from the most recent evaporation of sea spray within the pores of the aeolianite. Ions from the sea spray are carried in diluted aqueous solutions and these penetrate into the rocks and then evaporation and concentration of the salts occur until they eventually crystallise out. Earlier phases of halite are likely to have been dissolved during wetter conditions in the pore spaces and thus are not preserved. The salt crystals do not appear to be involved in weathering the deposit and are merely aiding in holding the clasts together.

DISCUSSION

In general, the differences in mean values of total cement, primary porosity and secondary porosity are far greater in

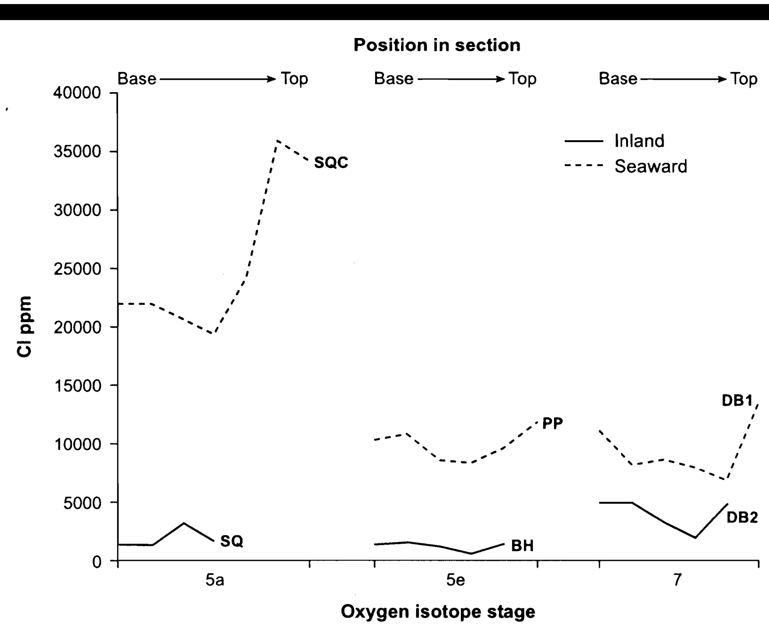

Figure 6. Plot showing the concentrations of Cl in ppm for the all the deposits studied in the sea spray zone and inland.

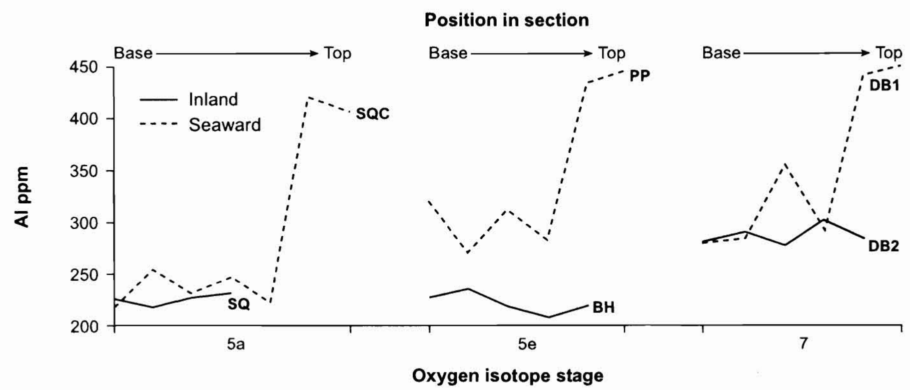

Figure 7. Plot showing the concentrations of Al in ppm for the all the deposits studied in the sea spray zone and inland.

Bermuda than found by McLaren (1995) in Jamaica, The Bahamas or Mallorca. This is likely to be because in Bermuda the comparison is between exposures in the spray zone compared to those not exposed, except from any solutions that may have infiltrated down through the sediments from the surface exposure. All the other sites, except one, studied earlier (in McLaren, 1995) have been exposed to sea spray to some extent. The exception is one of the samples from Jamaica that has been buried by up to 1.5 metres of Holocene dune sands. This deposit is very friable (12.2% total cement) and has undergone little diagenetic alteration.

Rossi-Manaresi and Tucci (1990) studying the effects of sea spray on building stones found that "dissolved calcite and gypsum transported from the inside of the stone crystallise close to the surface increasing the cohesion of a thin stone layer" (p98). On a larger scale, in an active diagenetic environment, this appears to be the same case for the aeolianites studied in Bermuda with dissolution of allochems, redistribution of supersaturated carbonate solutions (partially as a result of near surface evaporation) and precipitation of cements.

The role of salts in the stabilisation and cementation of dune sands at an early stage in their history has previously been suggested by Land *et al.* (1967), working in Bermuda. The salt crystals occupy pore spaces in the aeolianites as passive porefilling cement rather than contributing to weathering, which was also the finding of McGreevy (1985), who studied the effects of salt weathering in Carboniferous sandstones from near Ballycastle, Northern Ireland. The salts appear to aid cohesion rather than break down the aeolianites studied in Bermuda, which agrees with the findings of Goudie (1993) who concluded that NaCl has been shown to be ineffective in causing the breakdown of a number of different

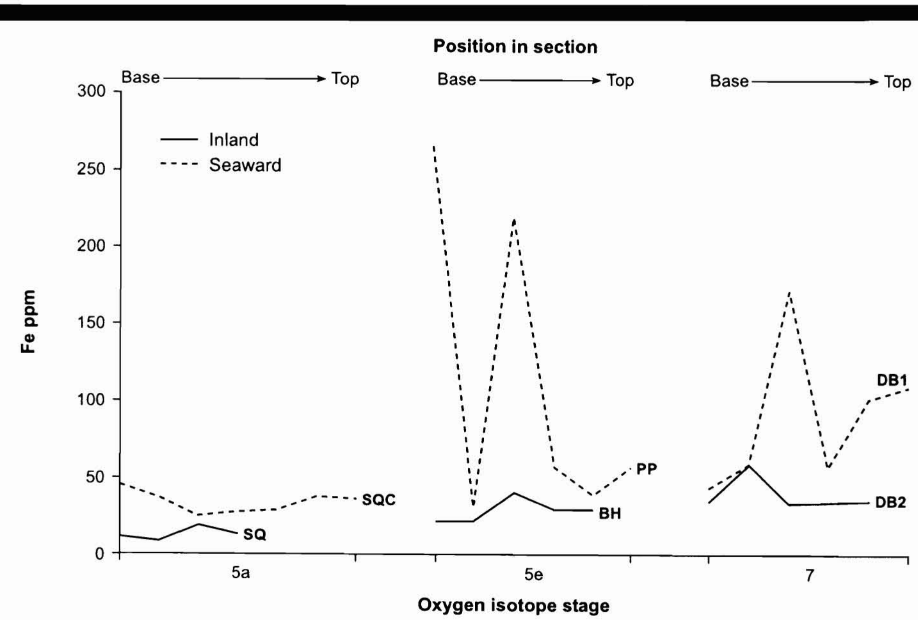

Figure 8. Plot showing the concentrations of Fe in ppm for the all the deposits studied in the sea spray zone and inland.

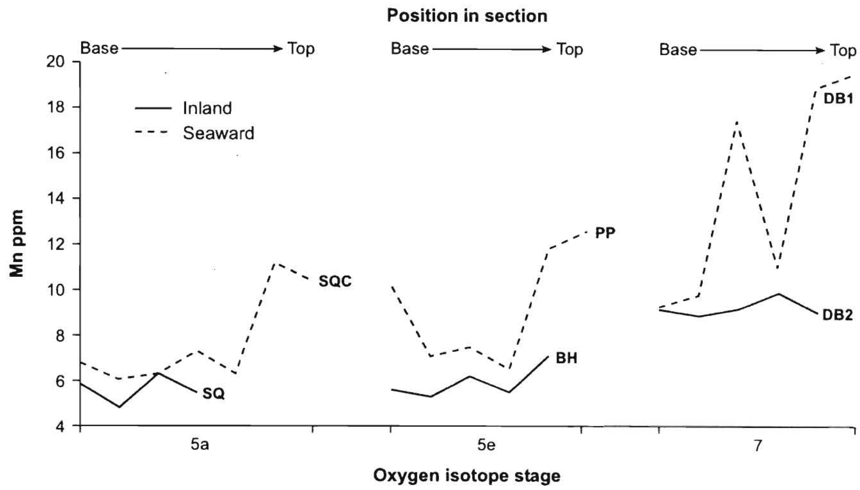

Figure 9. Plot showing the concentrations of Mn in ppm for the all the deposits studied in the sea spray zone and inland.

rock types (including limestones and sandstones). It may be that the pore spaces in the aeolianites are too large for salt weathering to occur on any significant scale. KOZLOWSKI (1990) looked at coarse-grained limestones and found that solutions moved readily both into and out of the rocks and so little weathering occurred. However, in fine-grained limestones the solutions were retained, and evaporation led to concentration and precipitation of salts, which caused more damage. AUGER (1990) also noted that rocks with low porosities were more prone to salt weathering.

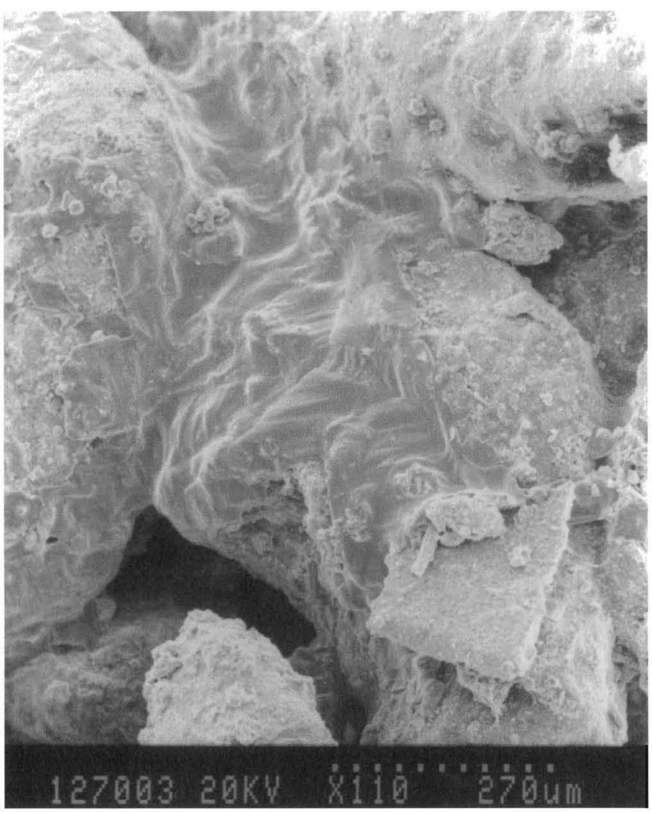

Plate 6 SEM image showing halite coating low-Mg rim cements in sample SQC6.

Plate 7 SEM image showing halite coating low-Mg rim cements and forming a meniscus bridge between two clasts, in sample DB1.4.

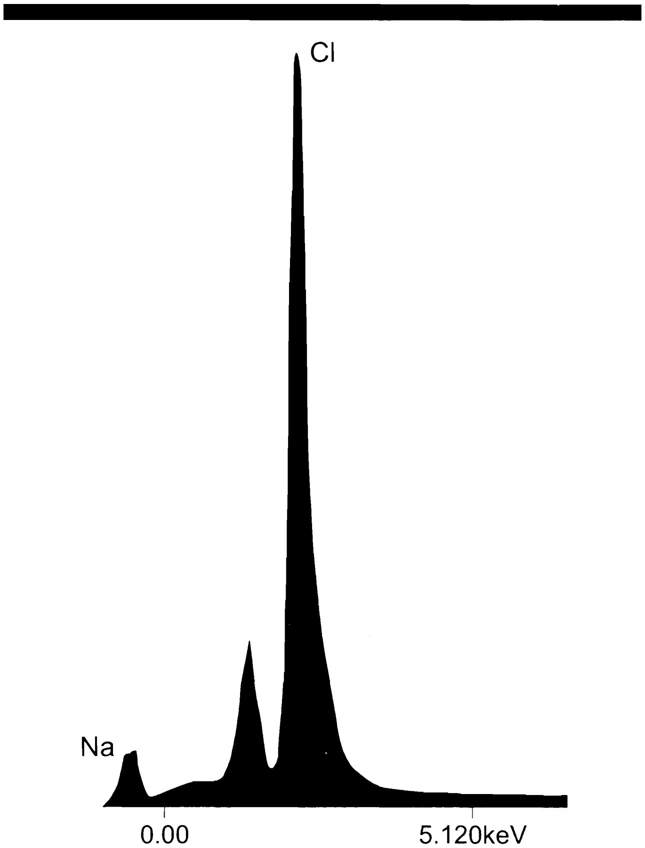

Figure 10. Plot displaying the chemistry of the halite crystals displayed in Plate 6.

PYE and MOTTERSHEAD (1995) studied the penetration of sea salts into a rock wall (clay-rich sandstone of Lower Carboniferous age) by investigating the distribution of NaCl beneath the weathering surface. They found that salt crystallisation and hydration pressures played a small role in weathering. They did not find crystalline salts in the rock but increased levels of saline elements were found. Possibly, the hotter (and frequently windy) conditions in Bermuda have resulted in greater levels of evaporation allowing the crystallisation of highly soluble halite as well as less-soluble calcite.

CONCLUSIONS

This study shows that Pleistocene aeolianite deposits in the spray zone tend to be better cemented, have higher levels of secondary porosity, lower primary porosities and a lower unaltered allochemical content than the same formations not exposed to sea spray. The statistical tests conducted show that, in most cases, the null hypothesis (that there is no significant difference between the mean values of total cement, primary porosity and secondary porosity in the deposits from the spray zone and inland) can be rejected with a 99% certainty. The processes, or rates of processes operating in the two different environments are not the same and it is likely that the spray zone is an area of 'accelerated + enhanced' diagenesis. As expected, there tends to be greater amounts of diagenetic alteration in the older deposits in both the aeolianites exposed to sea spray and those that are not, but this pattern is masked if only age is considered and the role of sea spray is ignored.

The same patterns are picked up in all three formations of different ages (Oxygen Isotope Stages 5a, 5e and 7), although the effects of sea spray seem to be slightly less apparent in the Rocky Bay Formation. This is because this deposit is facing northwards and is exposed to lower amounts of sea spray in comparison to the sample sites in the Southampton and Belmont Formations.

Geochemical studies have been conducted to identify what the effects of input of ion-rich spray solutions into the aeolianites are. More calcium is present in the spray zone and upwards towards the top of the profiles. From the thin section studies it can be seen that this is in the form of an increase in the amount of cements. The amounts of magnesium and strontium in the different deposits vary as a function of the different original allochemical contents. In addition, there are lower Mg and Sr values in the spray zone, probably as a result of greater dissolution of the contained allochems. Na and Cl are very closely correlated with very high values in the sediments in the spray zone. NaCl is also picked up in the SEM and EDX studies which show crystalline halite coating grains and post-dating carbonate cements. This indicates a relatively recent phase of evaporation and crystallisation of sea spray in the pore spaces of the aeolianites. Aluminium, manganese and iron are found in greatest abundance towards the top of profiles and in the sediments exposed to sea spray. The likely source of these elements is from terrigenous aerosols. The positive correlations between Ca and Na, Cl and Al may indicate that sea spray, including terrigenous aerosols play a role in the vadose diagenesis of the late Pleistocene aeolianites on Bermuda.

In terms of weathering, NaCl appears not to be involved in actively breaking down the deposits. Instead halite is simply aiding in infilling pores, with the pore spaces being too large for the halite crystals to exert any stresses that would cause mechanical disintegration.

The late Pleistocene aeolianites of Bermuda have been undergoing diagenetic alteration, in terms of dissolution of contained allochems, changes in porosity and the precipitation of cements, at varying rates dependant upon their location. The processes of diagenesis in the vadose zone at the coast where sea spray infiltrates into the dune pore spaces results in increased and accelerated rates of change in comparison to the same formations inland away from the exposure to sea spray. Studies looking at the rates of vadose diagenesis need to be aware of the influence of sea spray and to take into account the speeding up of processes of dissolution of allochems and precipitation of low-Mg calcite cements that occur in this environment.

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