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COASTAL SALT WEATHERING OF QUATERNARY EOLIANITE (BOZCAADA ISLAND) AND EOCENE SANDSTONE (GELİBOLU PENINSULA): THE CONTRIBUTION OF MICROANALYTICAL DATA

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ABSTRACT.- In this paper, factors controlling the diverse dissolution of Quaternary eolianite and Eocene sandstone in two different coastal environments in northwest Turkey were investigated by means of Energy Dispersive X-Ray Spectroscopy (EDX) coupled with Scanning Electron Microscopy (SEM), X-Ray Diffractometry (XRD), X-Ray Fluorescence Spectroscopy (XRF) analyses and thin section interpretations. With regard to governing agents of the weathering process, petrographic attributes, salt crystallization and biological impacts appear to be important. The weathered forms were found to be distinctive in size, shape and the degree of weathering owing to different mineral compositions of the host rocks and combined effects of sodium chloride (halite) and calcium sulphide (gypsum) crystallisation during the dry summer period when evaporation conditions dominate.

Key words: Eolianite, salt weathering, microanalysis, Bozcaada Island, Gelibolu Peninsula, Turkey.

INTRODUCTION

In coastal areas, sandstone weathering is controlled by a wide range of factors, such as petrography of the host rock, wind erosion, exfoliation, frost and thaw, biological activities and salt weathering. The impacts of crystallized sea salt on cavity development have been emphasized by several researchers (Evans, 1970; Mustoe, 1982; Mc Greevy, 1985). As an indurated coastal dune deposit, formed as a result of carbonate cementation, eolianite is also a kind of sandstone in petrographic composition and its mechanism of dissolution and resultant forms bear comparison with the weathered cavities that develop on coastal outcrops of various sandstones. However, compared to the numerous studies on weathering of coastal sandstone outcrops, our knowledge of the weathering of eolianite remains relatively limited.

In this paper, (a) we present two case studies from NW Turkey that shed light on factors controlling disintegration of Quaternary eolianite, located on the south coast of Bozcaada Island (lat. 39°48'51'' N to 39°48'42'' N, long. 26°00'12'' E to 26°00'26'' E) and (b) Eocene sandstones outcropping on the west coast of Gelibolu Peninsula (lat. 40°19'00'' N to 40°18'58'' N, long. 26°12'54'' E to 26°13'10'' E) to contribute to the discussions on coastal weathering of sandstones (Figure 1a). For both types of rock, we discuss the effects of physical disintegration induced by crystallization of sea salt, petrographic composition, and structural weaknesses based on field data, thin section interpretations and several analytical studies.

SITE DESCRIPTIONS

CAPE ZUNGUMA

Bozcaada Island is located 4 km west of the Biga Peninsula (western Turkey) and shows close geologic and geomorphologic relationships with that region. The geology of the island, as described by several authors (Erguvanlı, 1955; Kalafatçıoğlu, 1963; Saltık and Saka, 1972), consists of several lithologic units that range in age from Palaeozoic to Holocene. Palaeozoic metamorphic rocks (marble and schist) and underlying serpentine form the visible basement and are unconformably overlain by conglomerate, limestone and flysch of

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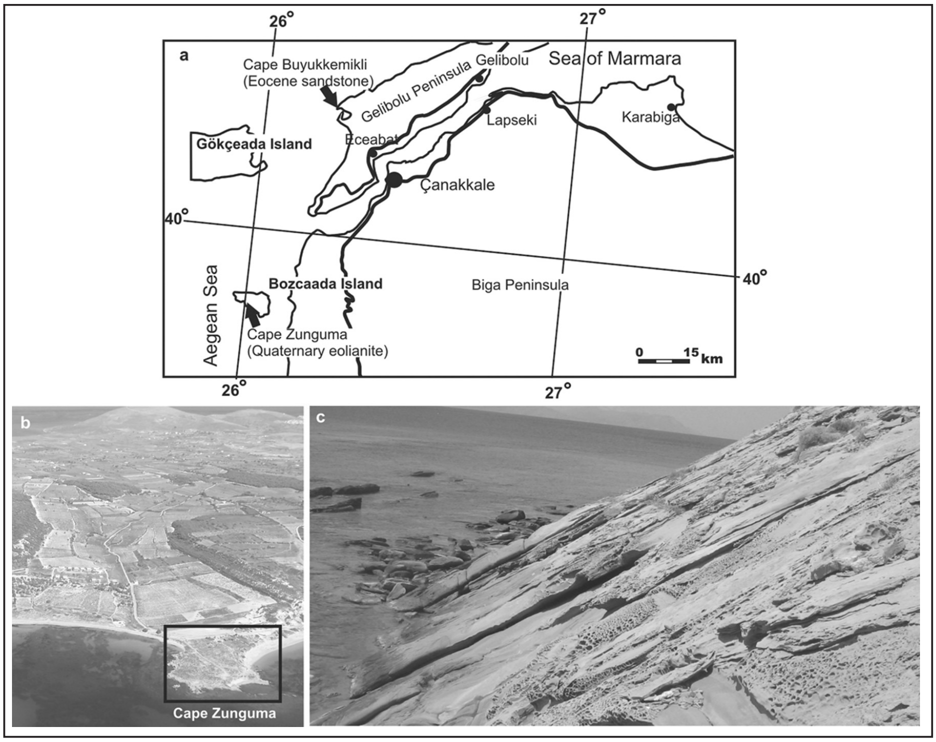

Figure 1- (a) Locations of the study sites; (b) oblique aerial photograph of the Cape Zunguma comprising Quaternary eolianite; (c) Eocene sandstones with honeycomb cavities at Cape Büyükkemikli.

Eocene age. Upper Miocene formations consist of conglomerate, sandstone, claystone, limestone and andesite. The western part of the island is occupied by recent coastal dunes. In previous publications, Cape Zunguma (Figure 1b), however, was not mapped in detail and was erroneously depicted as composed of Miocene deposits. A recent study, however, demonstrated that these outcrops consist of eolianite units of Late Pleistocene age, based on luminescence data (Kiyak and Erginal, 2009).

According to climatic data recorded at Bozcaada meteorological station (Geographical coordinate: 39°50' N and 26°04'E) for the period between 1975 and 2003, the area receives annual average precipitation of 462.5 mm. Maximum and minimum precipitations occur in winter (December: 89.4 mm) and summer (August: 5.5 mm) seasons. The average temperature is 15.4 °C. The coldest and the warmest months are February (8.3 °C) and July (23 °C). The island is one of the windiest areas in Turkey. The prevailing wind activity is from northeast. The number of stormy and strong windy days is 86.5 and 156.5, respectively.

CAPE BÜYÜKKEMİKLİ

Eocene sandstone crops out at the western end of the SW-NE-trending Gelibolu Peninsula in the northwestern part of Turkey (Figure 1c). Honeycomb cavities most commonly occur on the south-facing slope of Cape Büyükkemikli. The geology of the area and its surroundings has been previously studied by Önem (1974) and Sümengen and Terlemez (1991). The Eocene sandstones with honeycomb cavities crop out along the 3.3 km-long coastline of Cape Büyükkemikli. Elevations range from sea level to 15-20 m at the top of cliffs. Wave-cut platforms that can be observed about 30 m offshore to the south are conspicuously developed on seaward-inclined surfaces of sandstone ledges (Erginal et al., 2007).

In the absence of a meteorological station in the area studied, data obtained from the Gökçeada Meteorological Station (located 14 km west of the study area) indicates that the area receives an average precipitation of 737.9 mm per year. Maximum precipitation occurs in November, December and January. The amount of monthly average precipitation varies between 100 and 140 mm in these months. The area receives the lowest rainfall in the period from June to August, between 11 and 17 mm. The average temperature is 15.1 ºC. The yearly temperature range is from 24.6 ºC to 6.7 ºC in summer and winter periods, respectively. The frequency distribution and velocity of wind activity is predominantly from NE and SW.

METHODS

Several field surveys were carried out to note geo-environmental characteristics of the sites studied and to collect samples for analytical examination. Petrography of samples was determined by microscopic examination of thin sections. Energy Dispersive X-Ray Spectroscopy (EDX) and X-ray diffractometry (XRD) were used for major, minor and trace element characterization of samples collected. Scanning electron microscopy (SEM) was performed to characterize micro-porosity, micro-fractures and traces of micro-scale weathering on cavity walls. These analyses were performed in the mineralogy, petrography and technology laboratories of General Directorate of Mineral Research and Exploration, Turkey. To determine chloride ion concentration, the Mohr method (Skoog et al., 2000) was utilized. Ca, K, Mg and Na concentrations were determined by inductively coupled plasma-atomic emission spectroscopy (ICP-AES, Varian Axial Libery II Series).

RESULTS AND DISCUSIONS

MORPHOLOGIC CHARACTERISTICS OF WEATHERING FEATURES

Quaternary Eolianite

The eolianite, located on Bozcaada Island, comprises the N30E-aligned Cape Zunguma with a total area of 32120 m^2, constituting a promontory some 220 m long, backed by sandstone and limestone of Miocene age (Figure 1b). Several diagnostic features of this rock, such as foresets having angles between 15° and 20° and abundant content of rhizoliths as organo-sedimentary structures, reveal its eolian origin (Kiyak and Erginal, 2009).

Morphologically, the northern coast of the cape is dominated by 2-5 m-high sea-cliffs. Its western and southern parts are, however, formed by wave-cut platforms with elevations between 0 and 2 m, where weathered features occur (Erginal, 2008).

Weathered forms are represented mainly by dissolution cavities that display variable physical dimensions and shapes. In many places, these cavities are completely or partly occupied by sea water, thick salt accumulations within them are very common. From the wave splash zone to nearly horizontal surfaces, cavities occur preferentially on wave-cut platforms (Figure 2 a and b). Because of intensive dissolution, the surface of these platforms is quite irregular and marked by the presence of elongated cavities and irregular-shape connected pits, which are widespread along structural weaknesses that allow the penetration of sea water. Both diameters and depths of the weathered cavities range from a few cm up to over 1 metre. Honeycomb-like forms are absent.

Eocene sandstone

Weathering forms on the Eocene sandstones are characterized by the common presence of honeycomb cells (Figure 1c). Along the wave-splash zone (0-1 m) on the surface of dipping

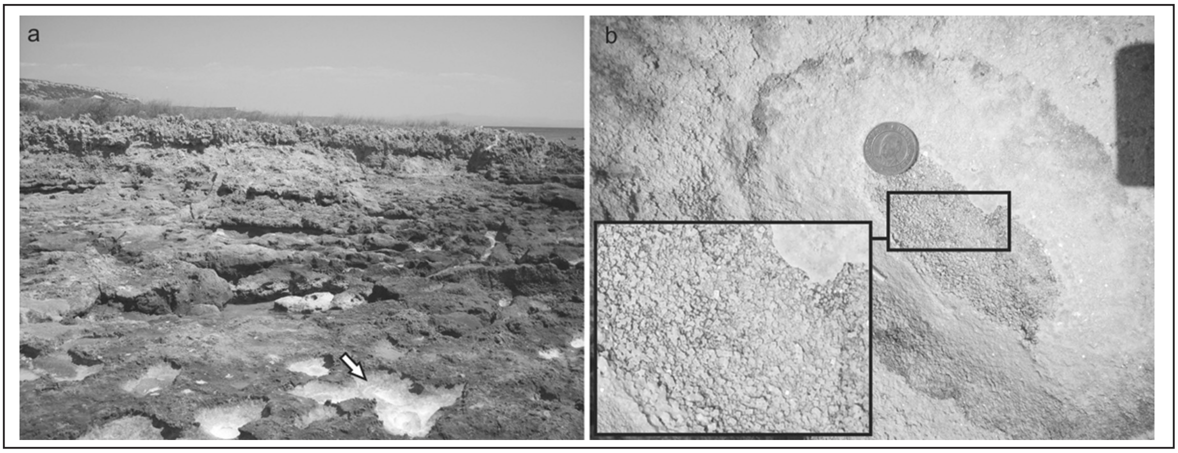

Figure 2- (a) View of numerous weathered cavities on wave-cut platforms; (b) a closer view of a cavity occupied by sea salt precipitates.

planes with N60ºE trend and 37º dip, the lengths of honeycomb cells range from 15 to 65 mm, widths from 15 to 50 mm, and depths from 10 to 45 mm (Erginal et al., 2007). Although they have circular or joint-controlled ellipsoidal shapes in general, the walls of cells are partly irregular due to the activities of rock barnacles, such as Semibalanus balanoides (Linnaeus 1758) and the gastropod Littorina neritoides (Linnaeus 1758).

In some places, larger cell sizes (length: 3.5 cm-10 cm, width: 2.5 cm-8 cm, and depth: 1.5 cm-6 cm) are present, likely related to the more abundant presence of rock barnacles. These bioeroders, especially Balanus populations, settled on southwest faces or in the bottoms of cavities conforming to east-west trending fractures. Closely spaced cells with sharp wall boundaries are well developed as a result of the enlargement of cavities through bioerosion of cavity walls. SEM analysis demonstrates that Balanus plays a significant biologic role in the weathering of the rock. Figure 3a shows evidence of this bio-erosion by the abundance of rock fragments surrounding the organism. It was also observed that the surfaces inhabited by Balanus are marked by shallow holes where traces of both chemical weathering and physical disintegration are present (Figure 3b).

MICRO-ANALYTICAL RESULTS RELATING TO SALT WEATHERING

Quaternary Eolianite

Thin section analyses show that the studied eolianite is lithic arenite in composition according to the classification of Pettijohn et al. (1987). The rock consists mainly of fragments of quartz, plagioclase, orthoclase, and, in lesser amounts, microcline, epidote, chloride and leucoxene. These mineral fragments constitute 40% of the petrographic composition. Several angular rock fragments such as quartzite, schist, micritic limestone, various magmatic rocks and microfossils are also found that make up the other 60%. Limestone fragments are predominant. All these components are found together by sparitic calcite and meniscus cements.

XRD data (Figure 4a) also demonstrated the widespread presence of calcite and quartz within the rock. The weathering residue deposited within cavity bottoms yields main peaks of quartz, calcite and, to a lesser amount, other accessory minerals such as rutile (Figure 4b). However, other minerals detected in thin sections were not identified in the XRD diffractograms, which reveal that the weathering of the rock is widely associated with dissolution of Ca.

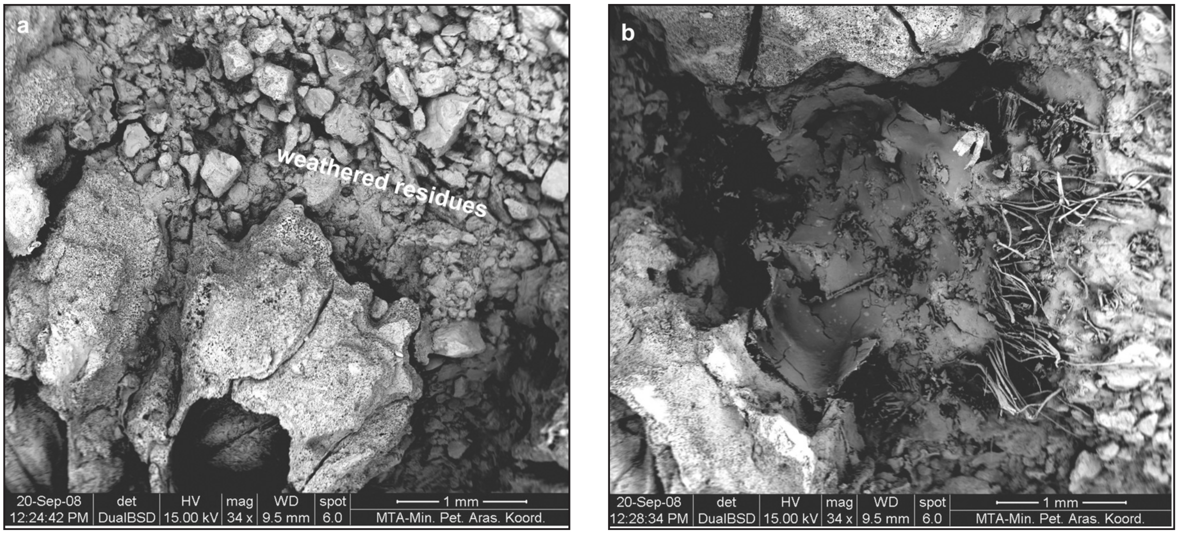

Figure 3- SEM images of Eocene sandstones; (a) weathered residues around, and (b) underneath a cavity caused by the rock barnacle Semibalanus balanoides.

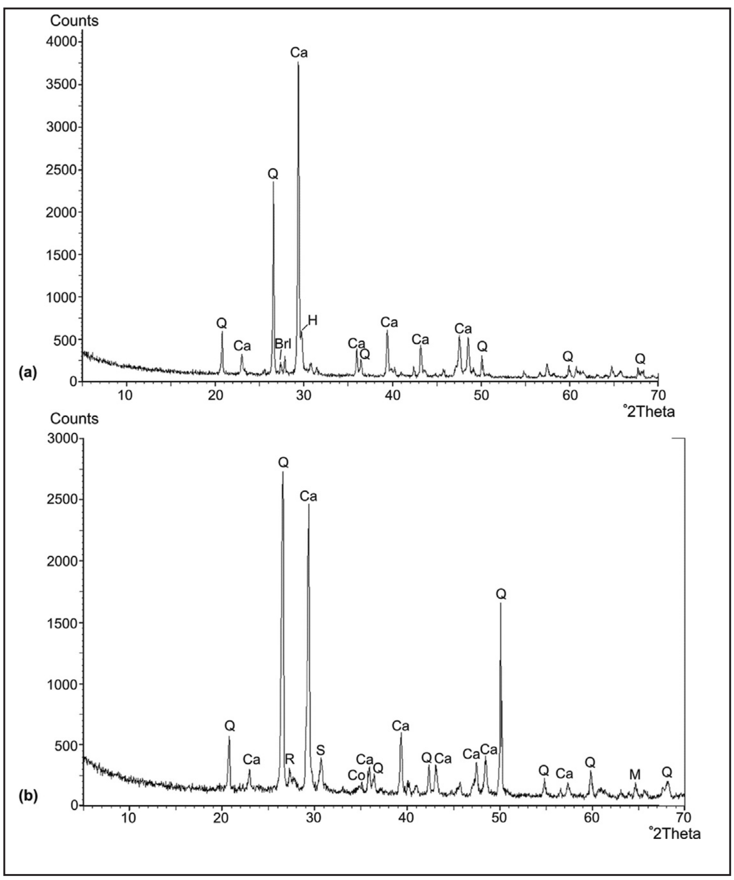

Figure 4- XRD diffractograms of eolianite (a) and its weathered product (b).

According to ICP-AES analysis, salt samples extracted from cavity bottoms contain Ca (3.546 ppm), K (12.450 ppm), Mg (7.942 ppm), Na (358.607 ppm). The Mohr method (Skoog et al., 2000), used to determine chloride ion concentration, revealed that Cl is found in an amount of 570 ppm. Based on these values, the analyzed salt is composed of NaCl (91 %), KCl (2.4 %), $CaCl_2$ (0.98 %) and $MgCl_2$ (3.3 %). The predominance of halite (NaCl) is confirmed by the EDX data, which also showed the existence of gypsum ($CaSO_4.2H_2O$). Thus, physical disintegration of eolianite is closely associated with the combination of halite and gypsum, as confirmed by SEM images (Figure 5a and b), showing a precipitated thick (max. 1 mm) salt crust over the rock surface and within micro-cavities. These observations indicate that the combined effects of halite and gypsum precipitated by the evaporation of sea water play an important role on the physical disintegration of eolianite in the study area, as previously emphasized elsewhere by Goudie et al., (1997), Goudie and Viles (1997) and Robinson and Williams (2000).

Eocene sandstones

To make a comparison with eolianite weathering, salt weathering on the surface of sandstone beds exposed on the Gelibolu coast was studied. The sandstone unit, underlain by siltstones with thin or laminated bedding features, is a yellow, fine-grained, calcite-cemented, moderately-sorted sub-greywacke according to Folk et al. (1970) classification. It is made up of predominantly quartz and plagioclase with trace amounts of biotite and muscovite. Lithoclasts of serpentine, chert and metamorphic rocks are also abundant. Beds are generally a few cm to 50 cm thick and dip from 30° to 50° toward the southeast. Honeycomb type of weathering is predominant (Erginal et al., 2007).

Salt crystallization induced by wind-enhanced evaporation of saline solutions deposited by sea spray is significant in development of honeycomb weathering in the coastal environment, as pointed out by several researchers (Mustoe, 1982; Matsukura and Matsuoka, 1991; Rodrigues-Navarro et al., 1999; McBride and Picard,

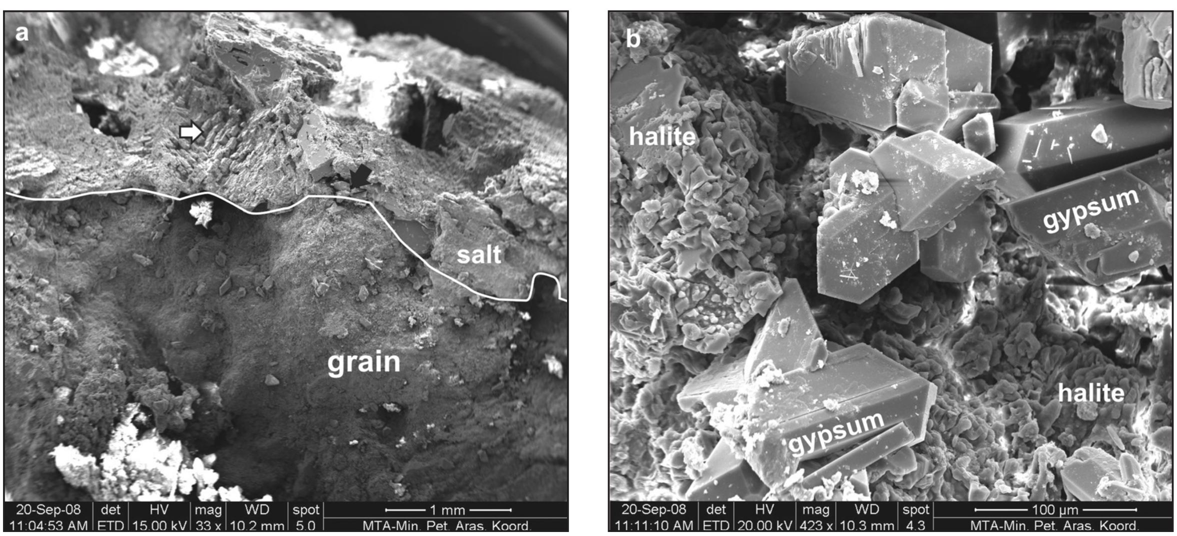

Figure 5- SEM images of eolianite; (a) the interface between salt crust and eolianite; (b) halite and gypsum crystals occupying micropores.

2004). EDX analyses carried out on salt samples collected from the honeycomb cells in August 2008, the driest period in this study area, demonstrated Na and Cl as the main constituents of the composition with total amounts of 39.31 % and 60.69 %, respectively. However, another sample yielded a more complex mixture comprising O (47.24%), Na (1.04%), S (22.46%), Cl (0.73%) and Ca (28.53%), suggesting the composition of gypsum ($CaSO_4.2H_2O$). Thus, it can be stated that salt precipitations involve both halite and gypsum, similar to those seen in the weathered eolianite.

SEM images (Figures 6 a and b) demonstrate the shapes and dimensions of halite and gypsum crystals. The salt encrustations with maximum thickness of 100Ìm were composed of cubic crystals of halite with sizes between 10 Ìm and 30 Ìm (Figure 6a). The interfaces between salt encrustations and the sandstone body are commonly voided and most of the voids are occupied by salt crystals. The cube-shaped crystals of halite are also covered with prismatic gypsum crystals, connected to each other with thin filament-like forms. The chain– shaped circular structures formed by halite crystals (Figure 6b) appear to coat the walls of weathering cells, which suggests that physical disintegration caused by pressure of crystallized salt within the micro-pores of the host rock is the most common mechanism of salt weathering (Evans, 1970; Bradley et al., 1978; Mustoe, 1982; Mc Greevy, 1985).

CONCLUSIONS

This study demonstrates that the Quaternary eolianites and Eocene sandstones from the study area exhibit significantly different coastal weathering features. In particular, the Eocene units are characterized by honeycomb weathering cells whereas the Quaternary eolianites lack honeycomb cells but display abundant, larger but more heterogeneous dissolution cavities, many of which have exploited structural weaknesses within the rock.

Precipitation of halite and gypsum from penetrating salt-spray appears to be the principal agent of destructive weathering in both types of deposit but physical bioerosion by molluscs

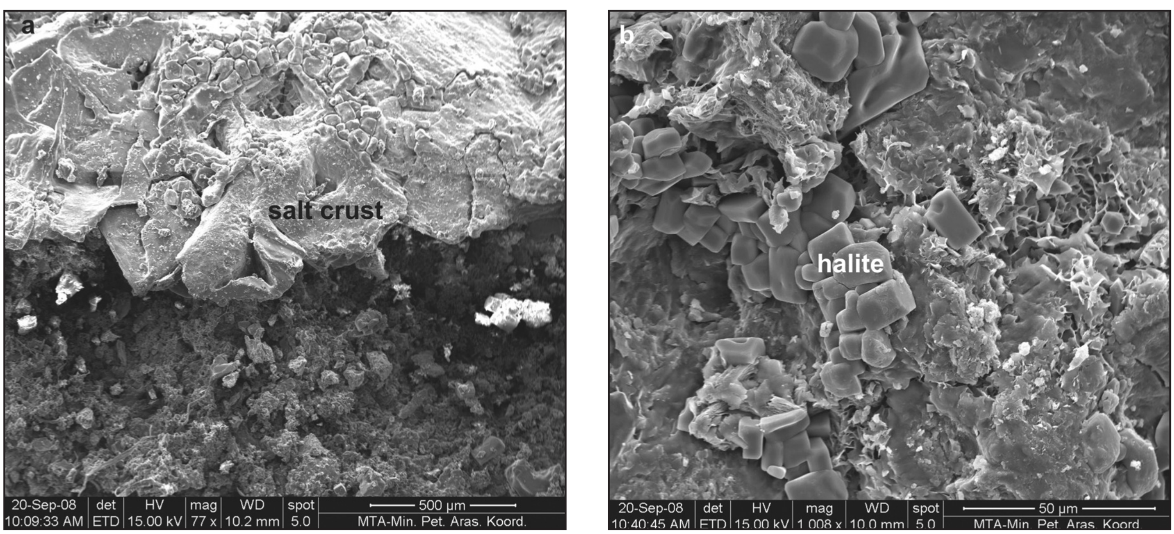

Figure 6- SEM images showing coastal salt weathering on Eocene sandstones; (a) the interface between salt crust (top) and sandstone; (b) arcuate arrangement of halite crystals on the wall of a honeycomb cell developed in micropores within sandstone.

(barnacles and gastropods) is also important in enlarging chemically formed cells, especially in the Eocene sandstones. In contrast, the close-spaced strata and cross-bed planes that characterize the eolianites favour leeward-drainage of impacting sea-water and saline spray. This feature, together with the higher carbonate content of the eolianites, leads to large-scale dissolution and rapid enlargement of weathering cavities in these Quaternary units.

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