Journal of Coastal Research	10	2	374–394	Fort Lauderdale, Florida	Spring 1994

Erosional Features of Coastal Beachrock and Aeolianite Outcrops in Natal and Zululand, South Africa

W.R. Miller and T.R. Mason

Joint Geological Survey–University of Natal
Marine Geoscience Unit
University of Natal
Durban 4001, South Africa

ABSTRACT

MILLER, W.R. and MASON, T.R., 1994. Erosional features of coastal beachrock and aeolianite outcrops in Natal and Zululand, South Africa. *Journal of Coastal Research*, 10(2), 374–394. Fort Lauderdale (Florida), ISSN 0749-0208.

The contribution of chemical processes to the erosion of beachrocks and aeolianites within the intertidal zone has long been a contentious issue. This paper briefly summarises previous work and describes new observations from the southeast coast of southern Africa. Field observations of isolated seawater bodies on the intertidal platform established a range of pH values, ascribed to diurnal variation. The contribution of biochemical processes to chemical erosion of beachrock is highlighted. Seventeen different erosive features occurring in coastal outcrops of beachrocks and aeolianites are described and illustrated. The majority of these erosional features occur on intertidal outcrops of beachrock/aeolianite, making a crude zonation of the topography possible. The physical dimensions and spatial distribution of erosional features within the intertidal and supratidal zones are described. Processes responsible for the formation of the erosional features include: physical erosion; chemical erosion; bioerosion; bioarmouring and algal induration. The possible modes of formation of each of the erosional features is discussed. Three different types of intertidal platforms occur on this coast: (1) Type 1 intertidal platforms comprise beachrock or aeolianite, sculpted by the retreat of a sea-level notch into a rocky headland; (2) Type 2 intertidal platforms comprise planed surfaces of beachrock or aeolianite which extend landwards under a cover of beach sand; (3) Type 3 intertidal platforms comprise multiple layers of seaward dipping beachrock which are preferentially eroded into a stepped appearance.

ADDITIONAL INDEX WORDS: *Intertidal platform, chemical erosion, supratidal zone, bioerosion, algal induration, carbonate sediments*

INTRODUCTION

Subtropical coastlines throughout the world are characterised by coastal outcrops of carbonate-cemented sediments in the form of beachrocks or aeolianites (SEISSER, 1974). A study carried out on such sediments at various localities along the Natal and Zululand coastlines in South Africa shows that a unique association of erosional phenomenon occur in these outcrops within the intertidal and supratidal zones. The aim of this study is to describe and illustrate the erosional features, to investigate the spatial distribution of the erosional features within the intertidal and supratidal zones, and to discuss the mechanisms responsible for the formation of the erosional phenomenon.

STUDY AREA

The west coast of South Africa from Natal into northern Zululand is characterised by intermittent outcrops of carbonate-cemented beachrocks and aeolianites of Holocene and Pleistocene age (COOPER 1991a,b; RUSSELL and MCINTYRE, 1965; RAMSAY, 1990, 1991; RAMSAY and MASON, 1990). Good exposures of these outcrops in a beach environment occur at Treasure Beach, Umdloti, Mission Rocks, Bat's Cave, Jesser Point, Mabibi, Black Rock and Bhanga Nek. These localities represent the study area for this paper, and their geographic locations are shown in Figure 1.

WATER CHEMISTRY AS AN EROSIVE AGENT

EMERY (1946) and COETZEE (1975a) suggested that chemical dissolution of the carbonate cement of lithified beach and dune deposits was caused by pH fluctuation of seawater trapped on the intertidal platform during the low tides. They further stated that the photosynthetic and respiratory cycles of marine algae were capable of adjusting the pH of seawater by addition or removal of carbon dioxide.

During the hours of sunlight, carbon dioxide is used up by photosynthesis and an increase in pH is expected: the reverse is expected at night when respiring algae release carbon dioxide into the wa-

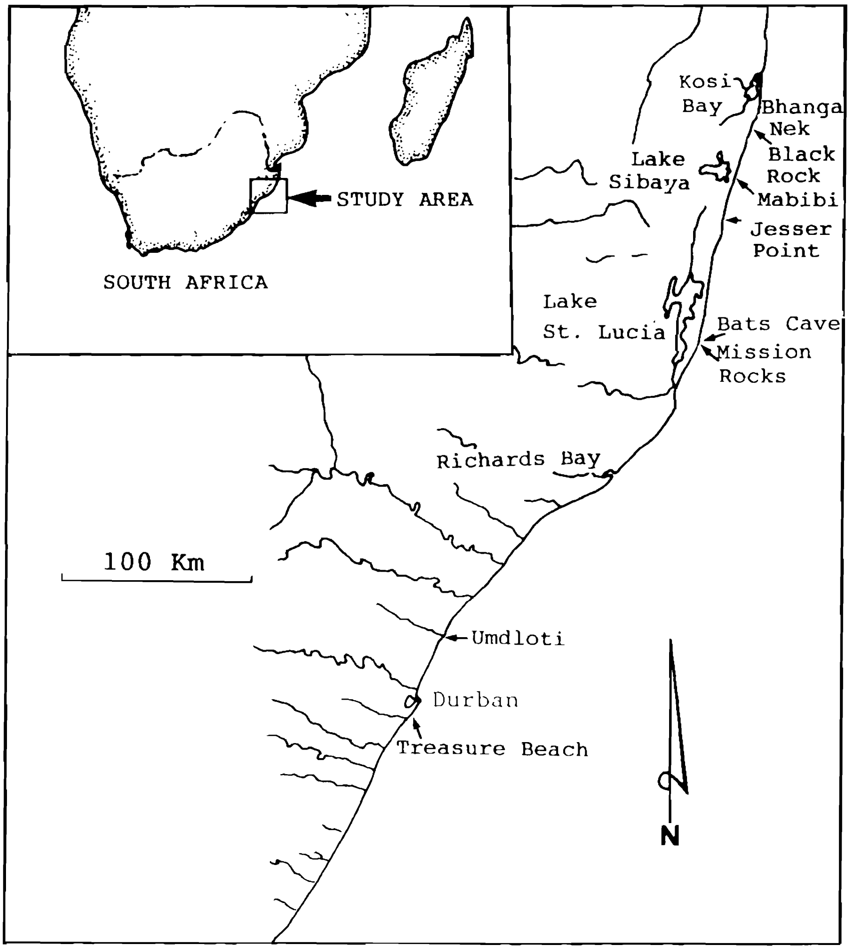

Figure 1. Map showing the geographic distribution of the eight study areas on the east coast of South Africa.

ter. EMERY (1946) stated that pH fluctuations were temperature aided, with carbon dioxide being more soluble in waters of lower temperature. This theory was tested by monitoring pH levels in selected potholes and other depressions on the intertidal platform at Bhanga Nek. Measurements were taken during the low tides with a portable Hanna Instruments HI 8314 pH meter in combination with a HI 1030B glass electrode.

Method

Five different sites were selected on the Bhanga Nek intertidal platform, each differing with respect to concentration of algae and volume of water contained. The pH levels of these sites were monitored at half-hour intervals when the tides were low during the day and at night. Buffer solutions (pH 7 and pH 10) were used to calibrate the instrument before each set of readings was taken. Precautions taken to insure that the buffer solutions did not become contaminated included:

(1) rinsing the electrode with distilled water before immersing it in the buffer solution;
(2) drying excess water from the electrode before placing it in the buffer solution thereby avoiding dilution;
(3) sealing of buffer solution containers and storing them in a cool place out of direct sunlight.

Results

It was found that the pH rose to maximum of 9.20 during daylight hours and fell to a minimum of 7.65 at night. These values represent a significant fluctuation from the pH of normal seawater which is of the order of 8.20. It was found that in small depressions (low volume) with dense algal growth the pH adjusted more quickly within a greater range of values. Other factors that influenced pH levels include:

(a) the temperature of the water trapped in the depressions
(b) air temperature
(c) the length of time the depression represented a closed system
(d) the time of day
(e) weather conditions

In considering the solubility of solid carbonates, it is the conversion of the carbonate ion (CO_3^{2-}) to the bicarbonate ion (HCO_3^-) that is primarily responsible for the dissolution of the carbonate minerals (RILEY and SKIRROW, 1965). Addition of carbon dioxide to the water leads to the reaction:

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$$

As pH falls, the carbonate ion concentration falls and the capability to take and hold the combining metal ions in solution is increased (RILEY and SKIRROW, 1965). Thus, if undersaturation occurs, the seawater can make up the deficit by taking ions from solid carbonates into solution. The lower the pH drops below 8.20 the faster the rate of dissolution will be, thus pH levels of 7.65 can be regarded as very corrosive in a solid phase carbonate environment. It must be emphasized that although this could represent a significant erosive mechanism, it is confined to bodies of water that support algal growth and represent a closed system during the hours of darkness on the low tide. This hypothesis is still being investigated by the authors.

Other workers such as KAYE (1957) have investigated the contribution of solvent motion to dissolution of solid carbonates. Kaye noted that with increased solvent motion, the rate of carbonate dissolution increased. Kaye regarded seawater in a turbulent state as representing a powerful solvent; he did not regard pH fluctuations as a prerequisite for carbonate dissolution but rather the degree of turbulence which he called the velocity factor. As evidence for this, he stated that undercut profiles of sea level notches occurred only in calcareous rock types and were absent in other rock types exposed in the intertidal zone.

EROSIONAL FEATURES

Armoured Rim

The armoured rim is the seaward extremity of the intertidal platform that is locally raised 10 cm–80 cm above the level of the rest of the planed surface. These features are often elongated in a coast parallel direction and tend to vary significantly in surface area. Armoured rims have been described by other workers. GUILCHER (1988) referred to these features as raised ridges while COETZEE (1975a) termed them *Lithothamnion* ridges. The armoured rim is a remnant of earlier levels of the intertidal platform, which has been preserved due to retarded rates of erosion. This feature undergoes slower rates of erosion than other parts of the intertidal platform due to the degree of protection afforded it by dense encrustations of barnacles (*Balanus* sp.), oysters (*Saccostrea cuccullata*) and marine algae such as *Lithothamnion* (COETZEE, 1975a) and *Porolithon* (GUILCHER, 1988). Other erosional features such as raised ridges, blowholes, potholes and solution basins are often superimposed on the armoured rim (see Figure 3).

Under-Cut

Under-cuts are the deeply incised, submarine profiles encountered on the seaward margins of intertidal platforms. Under-cuts were first described by FAIRBRIDGE (1950) who concluded that these features at Point Peron, Western Australia, were a remnant feature of an earlier sea-level still-stand at 3 m below present levels. In the authors' opinion, these are more likely to be contemporary solution features that preferentially exploit the softer beachrock/aeolianite under the armoured rim. The fact that rock surfaces are usually protected from physical processes by a thick covering of marine algae, and that freshly broken rock surfaces are quickly recolonised by these organisms reinforces this theory of solution weathering. The "softer" nature of the rock under the armoured rim has been documented by several workers (FAIRBRIDGE, 1950; GUILCHER, 1988).

The under-cuts can vary in height from 0.04 m–1.8 m and can extend landward for distances up to 4 m. Undermining leads to the generation of cracks on the surface of the intertidal platform. The cracks are dominantly coast parallel and are spaced at regular intervals. A subordinate set of coast-normal cracks can divide undermined areas into separate blocks giving the intertidal platform

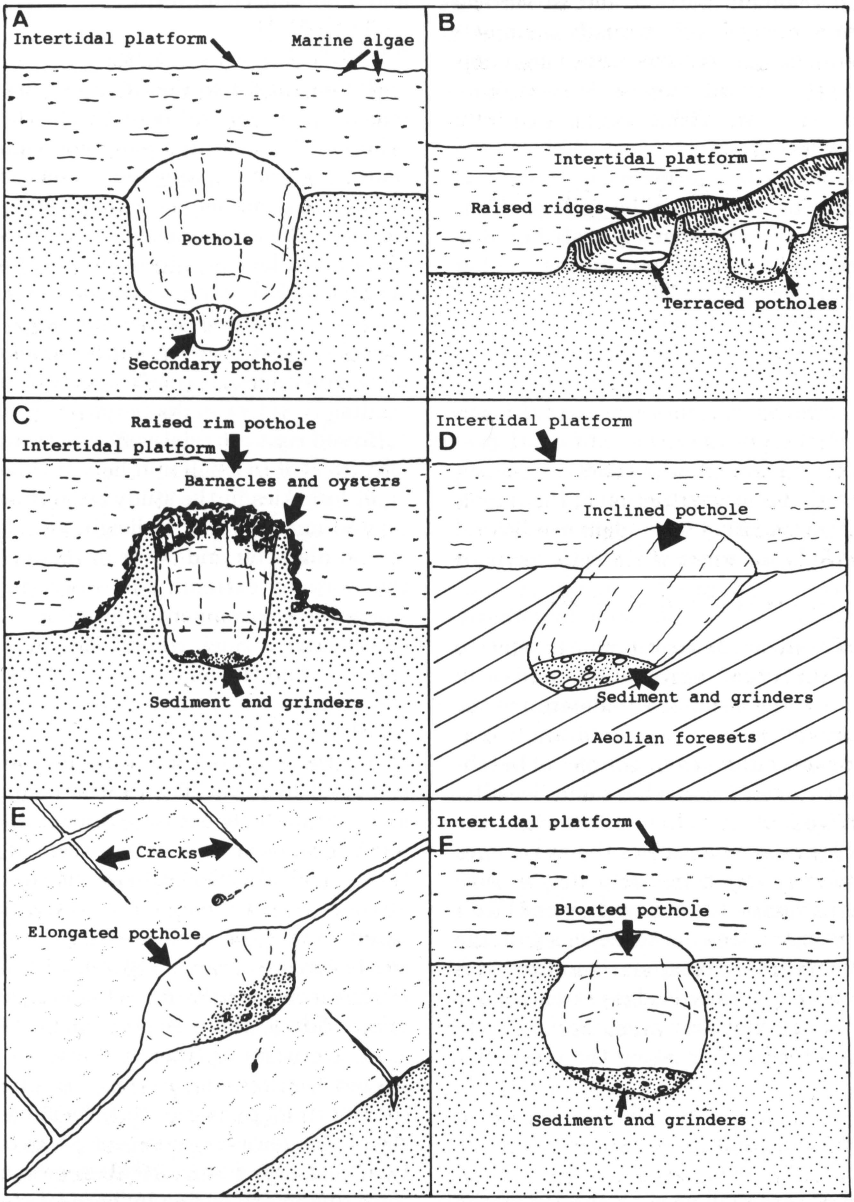

Figure 2. (A) Primary pothole with local deepening in the form of a secondary pothole. (B) Raised ridges and terraced potholes. Note that the terraced potholes extend below the base of the terraced pools. (C) Bio-armoured raised rim pothole. Note that the raised rim pothole extends below the intertidal platform in the immediate vicinity (dashed line), if this were not the case the feature would be termed a raised rim. (D) An inclined pothole that has formed due to erosive processes exploiting foresets in an aeolianite. (E) A sediment-filled elongated pothole that has formed due to the channelling of water along cracks in the intertidal platform. (F) Bloated pothole with sediment and grinders.

a "paved" appearance. These structural weaknesses facilitate the collapse of large slabs of the seaward margin of the intertidal platform and can also aid blowhole formation.

Raised Ridges

Raised ridges are low, sinuous crested, concave-sided features that form positive relief on the intertidal platform. In plan view, they have a bifurcating and rejoining pattern and in vertical section can be symmetrical to strongly asymmetrical (see Figure 2). The asymmetrical variety often form terraces and can trap or dam water on the intertidal platform during low tides to form terraced pools (see Plate 1). Most of the raised ridges are colonised by marine algae. The algae grow prolifically below the capillary fringe of terraced pools but are more sparsely distributed in more exposed areas that dry out during the low tides. Raised ridges attain 30 mm–200 mm in height and 1 m–30 m in length.

EMERY (1946) was one of the first researchers to describe these features and attributed their existence to stronger cementation around basin rims. BOWIE (1966) proposed that carbonate precipitation from seawater slowed erosive processes and contributed to the construction of the ridges. Considering that the pH of water dammed behind the raised ridges can rise to 9.2 during daylight and that some of the terraced pools dry up altogether, this appears to be a plausible hypothesis. There is, however, no petrographic evidence to support this theory of aggradation, and acid leaching of raised ridge samples to determine the carbonate content showed no significant variations in carbonate content from samples of beachrock/aeolianite taken from the same locality. COETZEE (1975a) and GUILCHER (1988) are of the opinion that the raised ridges owe their existence to algal induration which helps to slow erosive processes on the ridges. We believe that the latter explanation is more feasible since most of the raised ridges are coated with marine algae and, in many instances, the raised ridges extend above the capillary fringe that they dam, thereby making carbonate precipitation along the crests impossible.

Terraced Pools

Terraced pools are shallow pools formed by the damming effect of raised ridges. They usually occur in close proximity giving the impression of a series of steps (see Figure 4 and Plate 1). Terraced pools are generally flat-bottomed features and support prolific marine algal growth. Their shallow nature and the dense algal colonisation of the pools suggest that the dominant form of erosion is likely to be one of chemical carbonate dissolution. If the smaller pools become sufficiently deep to trap and retain sediment, pothole abrasion could become the dominant form of erosion and a pothole could form.

Raised Rims

Raised rims, like raised ridges, are steeply inclined, concave-sided features that form positive relief on the intertidal platform. Unlike the sinuous raised ridges, they are circular in plan view, exhibit higher relief and have a hollow centre giving them the appearance of small cones (see Figure 4 and Plate 2). These features were first described by FAIRBRIDGE (1948) who termed them micro-atolls. However, authors such as SCHEER (1971) suggest that the term micro-atoll should be reserved for subcircular coral colonies, not exceeding 6 metres in diameter.

Raised rims are relatively rare features and are only present in small numbers at three out of the eight localities in the study area. Raised rims attain 50 mm–400 mm in height and 100 mm–500 mm in diameter and occur in small clusters near the seaward extremity of intertidal platforms where the environment is protected from violent wave activity. Such conditions are normally encountered on the landward side of the armoured rim or in the lee of intertidal platforms that form headlands. The hollow centres of these features retain water during low tides and are therefore colonised by algae. The central depressions usually contain little clastic sediment and the dominant form of erosion within them is most likely to be chemical carbonate dissolution. The exterior of these features and areas of the interior that extend above the capillary fringe are usually encrusted with barnacles (*Balanus* sp.) and oysters (*Saccostrea cucculata*). As is the case with the raised ridges, there is no evidence from petrographic studies or from acid-leached samples to suggest that raised rims have been built up from the intertidal platform. It is the authors' opinion that these features represent areas of the intertidal platform that have been eroded at slower rates due to armouring by barnacles and oysters. The reason for their circular or near circular shape is, however, less clear. It is likely that raised rims originate as rejoining raised ridges that undergo erosional isolation, or as algal-indurated ridges around circular depression on the intertidal platform. Colonisation of areas of the raised ridge above the capillary fringe by barnacles and oysters, coupled with algal induration below the capillary fringe, ensure that these features are preserved as positive relief on the intertidal platform.

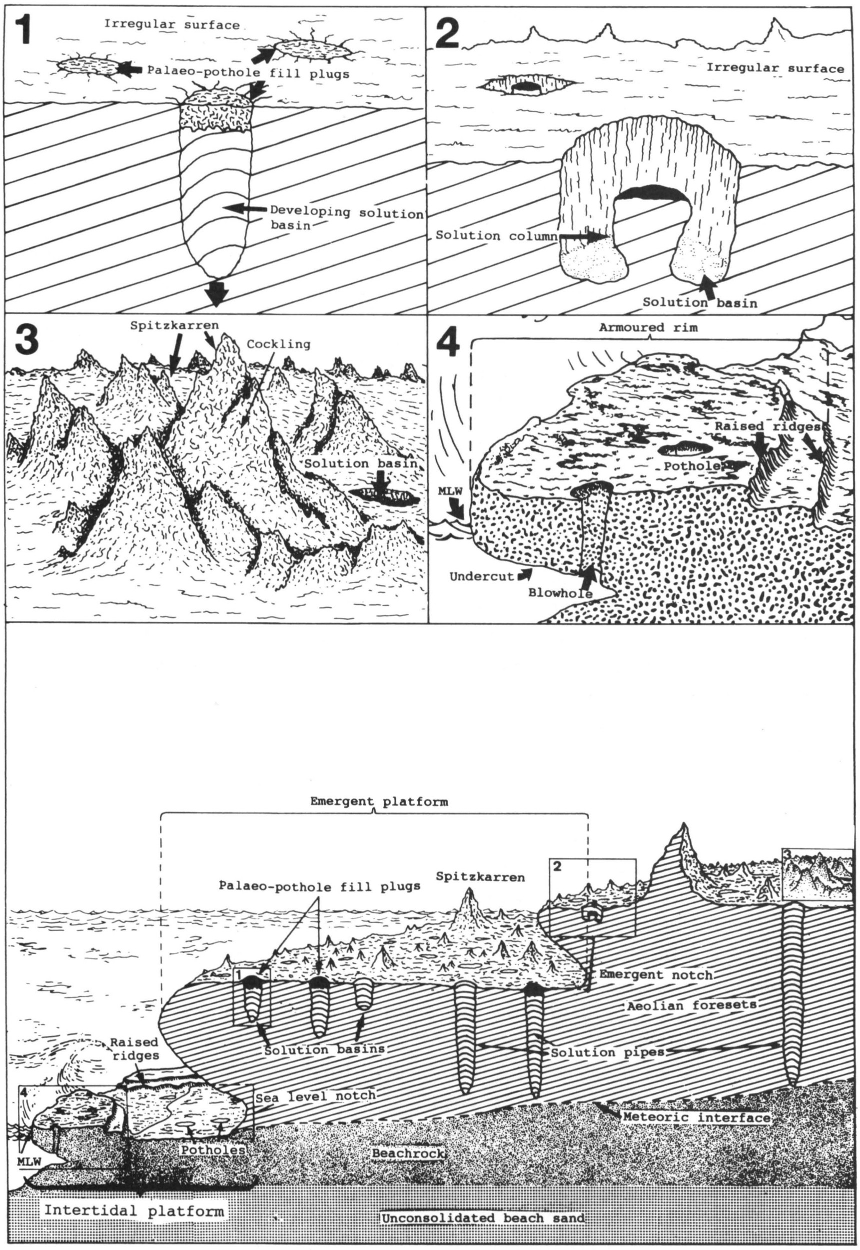

Figure 3. Type 1 intertidal platform which is retreating into a headland formed of aeolianite. The base of the sea level notch indicates the landward extremity of the intertidal platform. An emergent platform and emergent notch are evident in the supratidal zone. Erosional features within the intertidal and supratidal zones are highlighted in the insets. (1) solution basins and palaeo-pothole fill plugs; (2) solution basins and solution columns; (3) spitzkarren, cockling and solution basins; (4) armoured rim, undercut, blowhole, raised ridges and potholes.

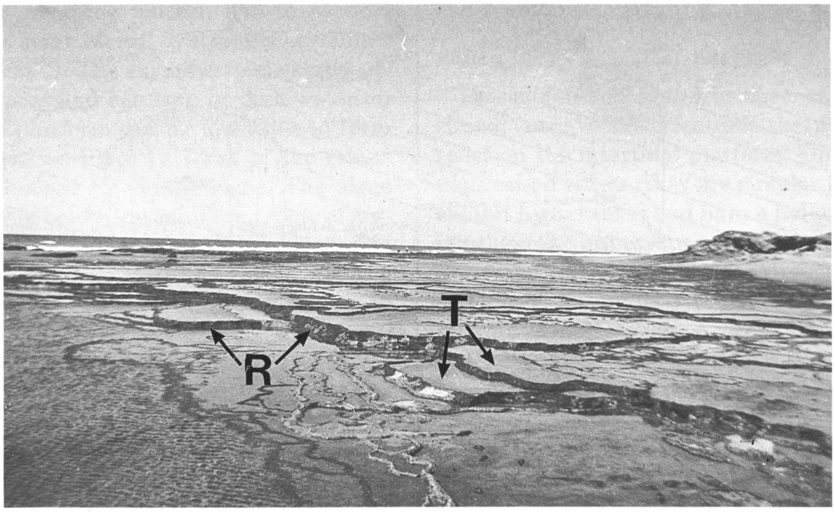

Plate 1. Raised ridges (R) and terraced pools (T) at Jesser Point, Zululand.

Potholes

Potholes are circular or near-circular depressions that have been physically ground into the rock (see Plate 3). Potholes are characterised by a diameter to depth ratio of less than 1:4 (ALEXANDER, 1932). Potholes are usually filled to some degree by sandy sediment or larger, well-rounded, rock fragments (grinders) but pothole walls are almost always colonised by marine algae. "Grinders" are pebbles of resistant minerals or rock types in excess of 2 mm in diameter which act as abrasive tools, powered by the energy of the surf. They physically grind and abrade the base of the pothole deeper into the substrate. Grinders are not a prerequisite for pothole formation since sandy sediment also acts as an effective abrasive tool when carried by water (ALEXANDER, 1932). Pothole dimensions are highly variable with depths varying between 0.05 m and 2.0 m, while pothole diameter ranges from 0.1 m to 3 m. Six different types of potholes were identified and are discussed separately.

Primary Potholes

Primary potholes are vertical depressions varying in cross-sectional profile from having near-vertical sides with a flat bottom to varieties that exhibit a rapid decrease in diameter with depth. Primary potholes are the most abundant type of pothole and are widely distributed about the intertidal platform: population densities can vary quite significantly (1/100 m^2–25/100 m^2). The highest pothole population densities are found immediately landward of the armoured rim with numbers dropping further landward.

Secondary Potholes

A secondary pothole is a local deepening of a primary pothole on a smaller scale (see Figure 2A). These features are described by ALLEN (1984) who termed them flutes. It is not uncommon for multiple secondary depressions to exist within the same pothole. They tend to evolve into a coalescent form of primary pothole.

Raised Rim Potholes

A raised rim pothole forms when the hollow centre of a raised rim erodes at a faster rate than the surrounding intertidal platform, resulting in the depression being lower than the intertidal platform in the immediate vicinity (see Figure 2C). Raised rim potholes are restricted to protected areas of the intertidal platform which are favourable for the formation of these features.

Inclined Potholes

Inclined potholes are non-vertical and form due to undercutting of a primary pothole by a more dominant erosive process acting in the direction

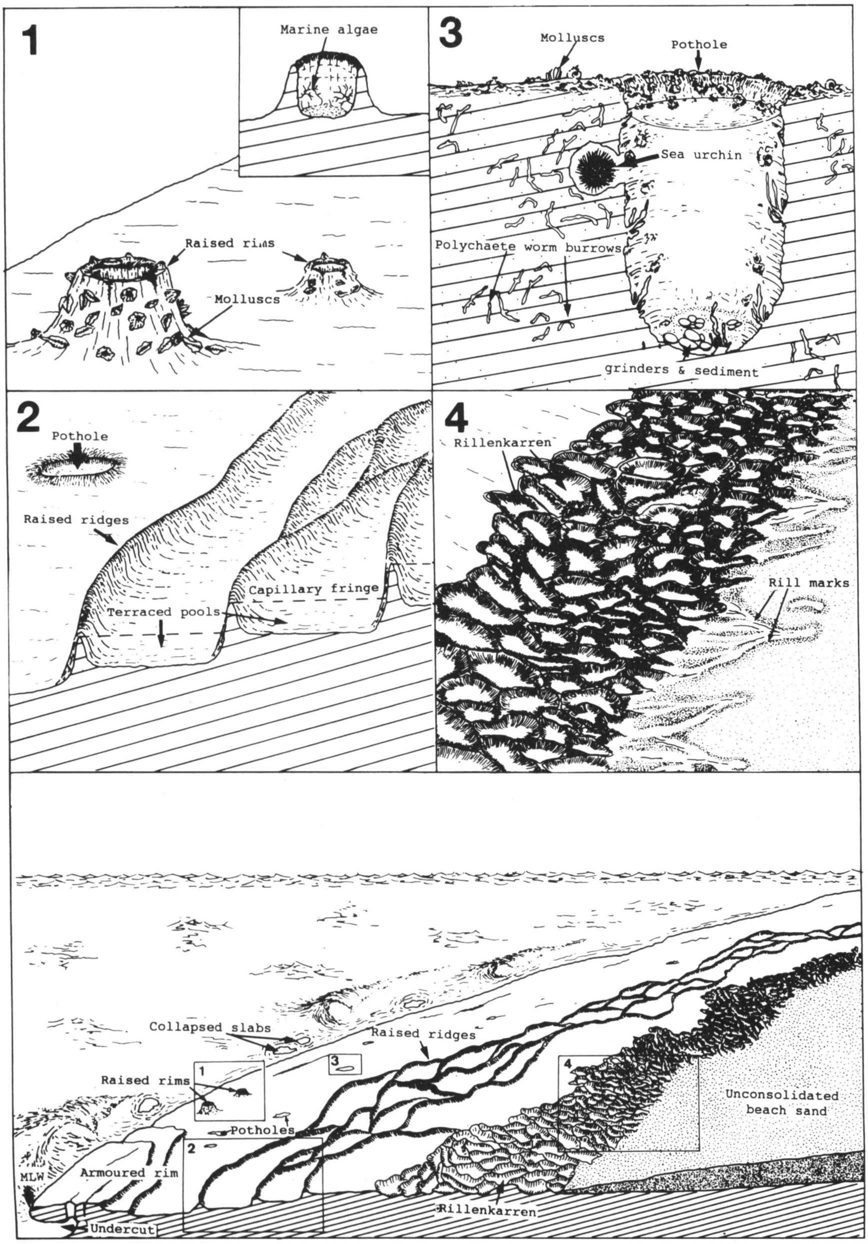

Figure 4. Type 2 intertidal platform showing the spatial distribution of erosional features on the surface of the exposed rock surface, under fairweather conditions. Erosional features highlighted in the insets include: (1) raised rims, note that the depth of the depression of this feature does not extend below the level of the intertidal platform in the immediate vicinity; (2) potholes, raised ridges and terraced pools, the dashed line indicates the capillary fringe of the terraced pools; (3) although physical erosion is the dominant form of erosion within potholes, borings by sea urchins and polychaete worms can modify the shape of their shape; (4) rillenkarren etched into the rock and rill marks formed in the unconsolidated beach sand.

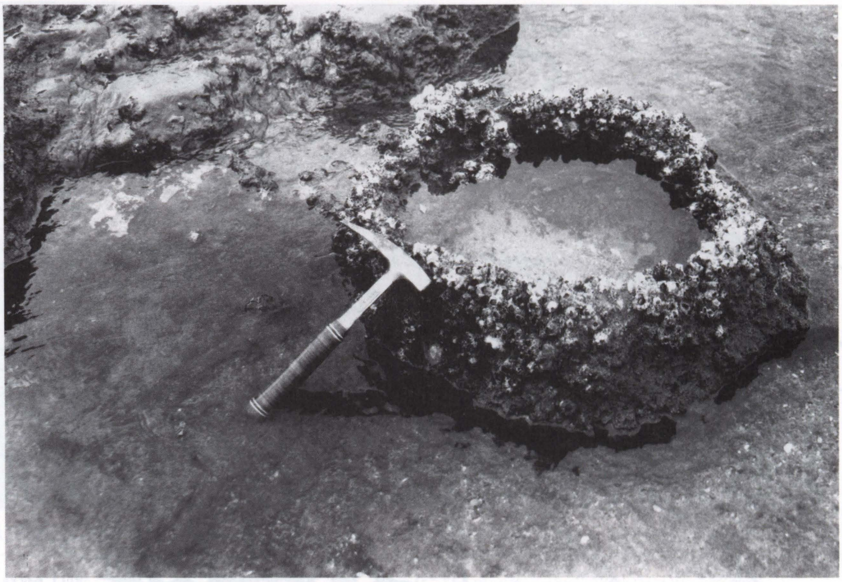

Plate 2. Raised rim at Jesser Point, Zululand. Note the barnacles (*Balanus* sp.) which encrust the outside of this feature.

of the undercutting, or by erosive processes exploiting structural weaknesses such as joints or planar foresets within the host rock (see Figure 2D).

Elongated Potholes

Elongated potholes are primary potholes that have been modified in plan view due to an erosive

Plate 3. Potholes with sediment and grinders at Jesser Point. Note the slightly raised rims (R) on some of the potholes.

Plate 4. Rillenkarren at Bhanga Nek, Zululand.

process being more dominant in one direction. The most common cause of elongated potholes is a 180 degree reversal of tidal currents. Elongated potholes can also form where tidally generated currents are channelled by joints or other areas of lower relief to flow in one direction off the intertidal platform (see Figure 2E).

Bloated Potholes

Bloated potholes are characterised by an increase in diameter with depth (see Figure 2F). They resemble huge examples of the ampulla-shaped trace fossil *Gastrochaenolites*. The increase in diameter with depth may be due to a number of reasons, including:

(a) a more efficient lateral component of grinding as the pothole is deepened;
(b) an excess of sediment in the pothole which prevents effective vertical grinding;
(c) carbonate dissolution being more active on the walls of the pothole due to the presence of a sediment layer on the floor of the pothole;
(d) bioerosion by molluscs and echinoderms which colonise pothole walls.

Terraced Potholes

Terraced potholes form when a terraced pool becomes deep enough to retain sediment thus making pothole abrasion possible. A terraced pothole can be distinguished from a terraced pool by the depth of the depression related to the raised terraced height (see Figure 2B). To be identified as a terraced pothole, the depth of the depression must exceed the profile height of the adjacent raised terrace.

Rillenkarren

Rillenkarren are shallow, sinuous, round-bottomed troughs which occur in close proximity and are separated by sharp sinuous crested ridges (ALLEN, 1984). Rillenkarren are seldom deeper than 150 mm and vary between 80 mm and 500 mm in width and between 180 mm and 1,000 mm in length. Rillenkarren formation is restricted to the fairweather interface between intertidal platforms and sandy beaches. These features can be strongly to moderately elongated and are oriented normal or at small angles to the beach–intertidal platform interface (see Figure 4 and Plate 4).

Rillenkarren formation on the intertidal platform is related to a combination of chemical and mechanical erosion. Meteoric water seeping through the coastal dune cordon and under the cover of unconsolidated beach sand emerges at the beach–intertidal platform interface *via* numerous regularly spaced rill structures (see Plate

Plate 5. Rill marks at the beach/intertidal platform interface at Bhanga Nek, Zululand.

5). Although there is mixing between meteoric and receding seawater during the low tide, the water escaping from the rill structures is likely to be undersaturated with respect to carbonate and, therefore, capable of chemical erosion. It is the authors' opinion that chemical erosion is the dominant form of erosion during low tides; however, the scarcity of marine algae together with the fact that the rock surfaces are smooth and polished testifies to the fact that reworking of clastic beach sediments on the high tides also contributes to rillenkarren development.

Sea Level Notches

Sea level notches are deeply concave profiles that occur on the landward margin of intertidal platforms that are eroding back into a headland consisting of carbonate-cemented sediments (see Figure 3 and Plate 12). The base of the sea level notch indicates the mean low water mark and is thus an important sea level indicator. If a sea level notch is abandoned above the mean high water mark due to a regressive event in such a manner that the characteristic undercut profile is preserved, the feature can then be termed an emergent notch (see Figure 4).

A combination of chemical, mechanical and bioerosion are operative within the intertidal range of the sea level notch. Above the mean high water mark, bioerosion by chitons, browsing molluscs and boring molluscs feeding on endolithic algae can account for rates of denudation of greater than 1 mm per year (KIRK 1977; KELLETAT, 1989; VITA-FINZI and CORNELIUS, 1973). As a result of bioerosion, the vertical extent of the sea level notch can be more than double tidal range (KELLETAT, 1989).

Linguoid Ridges

These features are similar in appearance to spur and groove topography found on tropical reef margins (GUILCHER, 1988). The lingoid ridges are built on a smaller scale, and the grooves carved into the ridge are not as strongly elongated as the spur and groove counterparts found on reefs (see Figure 5, Plate 13 and Plate 14). These physical features give the ridge a linguoid appearance in plan view. The linguoid ridges are confined to the laminated beachrock exposures (see Type 3 intertidal platform). The linguoid ridge is a remnant feature that results from longshore currents preferentially removing beachrock on the landward side of beachrock outcrops due to:

(1) structural weaknesses;
(2) lack of biological induration (*e.g.*, algae and molluscs);

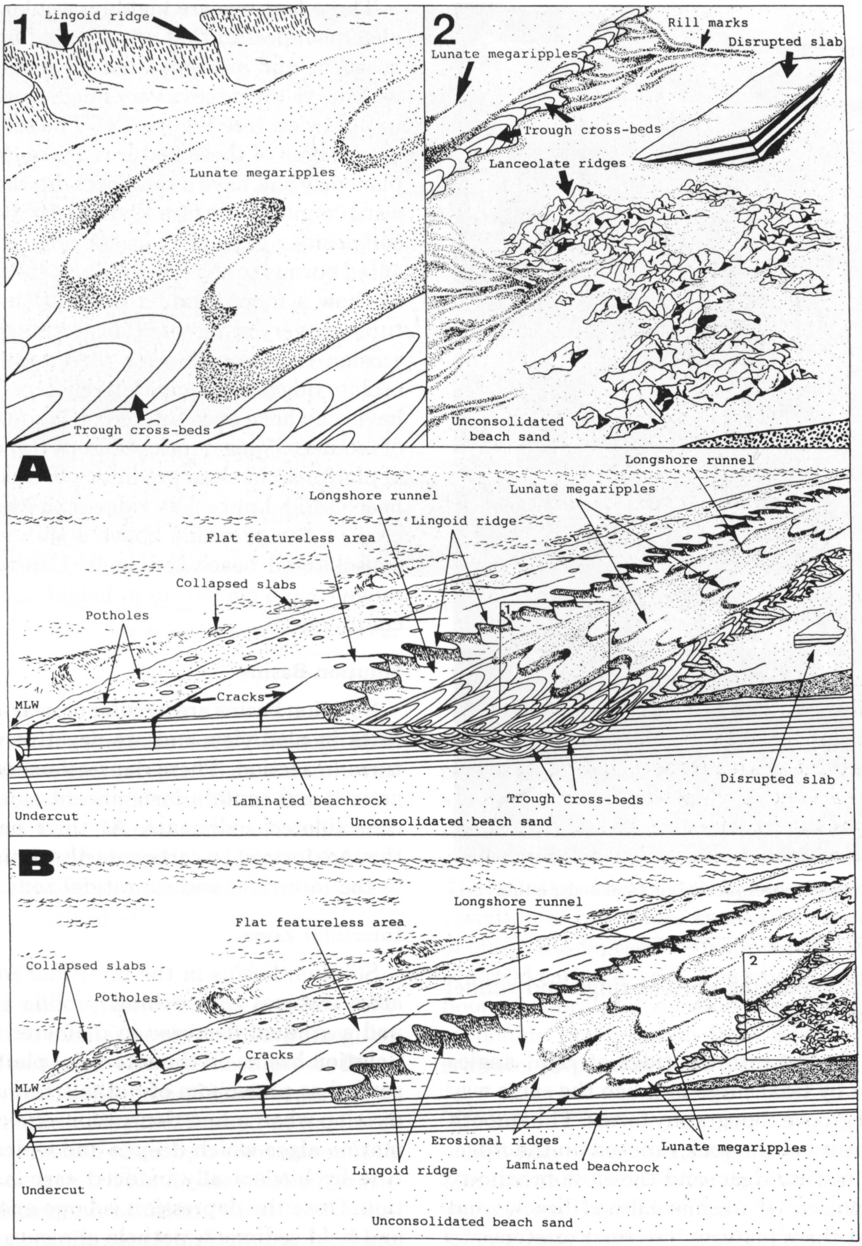

Figure 5. Type 3 intertidal platform showing the characteristic flat lamination that dips gently seaward. Two varieties of this type of intertidal platform are evident: (A) shows how longshore runnels form due to erosional exploitation of a palaeo-ridge and runnel structure; (B) shows how the longshore runnels form due to differential erosion of beachrock adjacent to beach sand. Features highlighted in the insets include: (1) the lingoid ridge, lunate megaripples which have formed in the unconsolidated sediment moving along the longshore runnel, trough cross-beds of the lithified palaeo-ridge and runnel structure; (2) disrupted slabs, lanceolate ridges, rill marks, lithified trough cross-beds and lunate megaripples.

Plate 6. Lanceolate ridges protruding from under a thin cover of beach sand.

(3) currents exploiting ancient ridge and runnel systems.

Grooves are cut into the ridge at right angles to the coast by tidal surge in much the same way as spur and groove topography forms. The smooth polished nature of the rock exposed on the ridge, the lack of marine algae, and the close proximity to large amounts of unconsolidated beach sand suggest that these features owe their existence to purely physical processes. The longshore currents which are channelled by the runnel created on the landward side of the linguoid ridge are capable of erosion and are probably responsible for the lack of elongation exhibited by the grooves in the ridge. The linguoid ridge attains heights ranging from 30 cm–80 cm and the grooves which adorn this feature are characteristically wider (50–150 cm) than they are deep (15–80 cm).

Lanceolate Ridges

These features are highly irregular ridges (single or composite) that are oriented normal to the coastline and are separated by irregular furrows which give the ridges a very rough lanceolate shape in plan view (see Figure 5.2). The seaward-facing extremities of these features are more pointed in plan view and have a shallower dip than the landward counterparts (see Plate 6). In the case of the composite ridges, the longest ridge is always oriented normal to the coastline and the shorter ridges show a more random orientation. These features are very water worn suggesting that physical erosion is responsible for their formation. Lanceolate ridges are comparatively rare features and have only been encountered on landward margins of laminated beachrock outcrops (type 3 intertidal platform) in close proximity to unconsolidated beach sand. Lanceolate ridges can form solid outcrop or can protrude above a thin cover of unconsolidated beach sediment. Lanceolate ridges range from 5 cm–40 cm in height and 15 cm–120 cm in length.

Solution Basins

Solution basins are circular or near-circular features in plan view and are negative vertical features in section. These depressions support algal growth and contain insignificant amounts of unconsolidated sediments. As their name implies they are formed by carbonate dissolution and form in the intertidal and supratidal zone.

Intertidal Zone

Solution basins in the intertidal zone are negative features that exhibit prolific algal growth and a gradual decrease in diameter with depth. Solution basins on the intertidal platform are regarded as precursors of pothole formation. They develop when minor depressions are colonised by marine algae which deepen and widen the structure by biogenically induced carbonate dissolution. Once the depression is large enough to trap and hold sediment, pothole abrasion commences and this can become the dominant mode of erosion. Intertidal solution basins vary in diameter from 0.05 m to 1.5 m and from 0.02 m to 0.04 m in depth. A diameter:depth ratio of 1:0.35 was used to distinguish potholes from solution basins on the intertidal platform in the study area. This value was chosen as most depressions plotting below this value are almost entirely covered in marine algae: this suggests that mechanical erosion

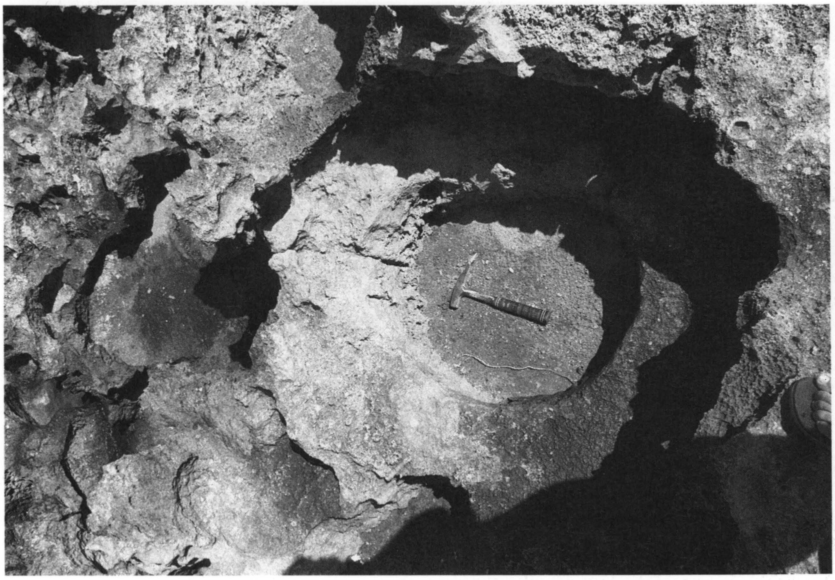

Plate 7. Flat bottomed solution basin in the supratidal zone at Black Rock, Zululand. Note the highly pitted surface of the host rock (aeolianite) which is characteristic of solution weathering.

is not active within these features. Although this is a generalisation and exceptions do occur, it was noted that depressions plotting below the threshold value were not effective sediment traps and usually contained little clastic sediment. This reduces the likelihood of mechanical erosion being the dominant agent of erosion.

Supratidal Zone

Supratidal zone solution basins are generally steep-sided and exhibit very rough and irregular internal side walls and a smooth bottom (see Plate 7). The supratidal solution basins are regarded as embryonic solution pipes (discussed in next section) and are characterised by a diameter: depth ratio of less than 1:4. This diameter: depth ratio is used to distinguish solution basins from solution pipes within the supratidal zone since physical erosion in circular depression is not possible below this value (ALEXANDER, 1932). The threshold value used to distinguish solution basins from potholes in the intertidal zone (*i.e.*, 1:0.35) is not necessary in the supratidal zone as potholes abandoned above the mean high water mark automatically revert to solution basins. Supratidal solution basins range in diameter from 0.1 m to 0.6 m and from 0.1 m to 2.4 m in depth.

Solution basin development occurs where depressions in the calcareous sandstone hold water and support algal growth. The water contained in the depressions can be rainwater or seawater spray generated by waves breaking in the intertidal zone. The solution basins develop in response to the variation of pH values caused by respiring algae or due to the depressions trapping rain water which is a mild carbonic acid. The smooth nature of the floor of supratidal solution basins suggests that carbonate precipitation from minor amounts of seawater trapped in these features is also possible.

Solution Pipes

Solution pipes are strongly elongated, negative features that are circular in plan and vertical in section (see Figure 3). These features form in carbonate-cemented sandstones in the supratidal environment and are characterised by a diameter: depth ratio of greater than 1:4. Solution pipes exhibit a gradual decrease in diameter with depth and highly irregular walls line the interior of the pipe. Solution pipes in the study area range from 200 mm–970 mm in diameter and vary in depth from 1,000 mm–10,770 mm, a maximum diameter: depth ratio of 1:23.3 was recorded at Black Rock. Solution pipes were described by TINLEY

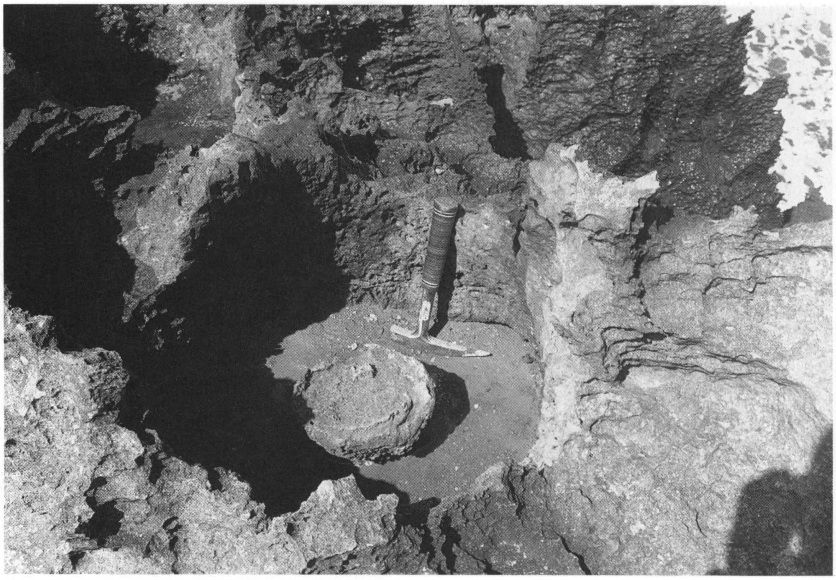

Plate 8. Solution column in a flat bottomed solution basin in the supratidal zone at Black Rock, Zululand.

(1987) who attributed the formation of these features in an aeolianite at Pomene, Mozambique, to solution weathering along calcretised tree stem channels. As evidence for this hypothesis, he stated that all pipes were vertical and exhibited a more resistant concentric lining which gave the resemblance of tree trunks. COETZEE (1975b) was of the opinion that the solution pipe linings at Pomene were secondary carbonate precipitates brought about by biogenic processes or by evaporation of seawater.

Solution pipes form when potholes, solution basins, or other depressions are abandoned in the supratidal environment after a marine regression. The abandoned depressions now on an emergent platform are deepened by chemical dissolution of carbonate cement caused by vertical percolation of slightly acidic solutions (COETZEE, 1975b). The erosional agent may be rainwater (mild carbonic acid) or water subject to biogenically induced pH fluctuations. The pothole fill which lithifies post-regression, often remains as a plug of palaeo-pothole fill at the top of a developing solution pipe (see Figure 3.1 and Plate 9). The reason for the induration and enhanced erosional resistance of the palaeo-pothole fill is unknown but may be related to the younger age of the carbonate cement. The maximum depth to which a solution pipe can develop is controlled by the meteoric interface where carbonate precipitation occurs and beyond which solution pipes cannot develop (COETZEE, 1975b).

Solution Columns

These are columnar features that form positive relief on the floor of steadily descending solution pipes or solution basins in the supratidal zone. Solution columns are circular or spherical in plan and columnar in section (see Figure 3.2 and Plate 8). Solution columns were only encountered at Black Rock where they occurred in flat bottomed solution basins and attained dimensions of up to 250 mm diameter and 150 mm height.

Solution basins within the spray zone retain water and thus support algal growth. It is likely that algal induration of the central portion of the solution basin floor results in slower rates of denudation and the development of a solution column.

Emergent Platforms

Emergent platforms are ancient intertidal platforms that have been abandoned above the mean high water mark by a regressive event. These features are characterised by a bench shape in section and a planed-off upper surface. These characteristics are often obscured by solution weathering features such as cockling and spitzkarren (see lat-

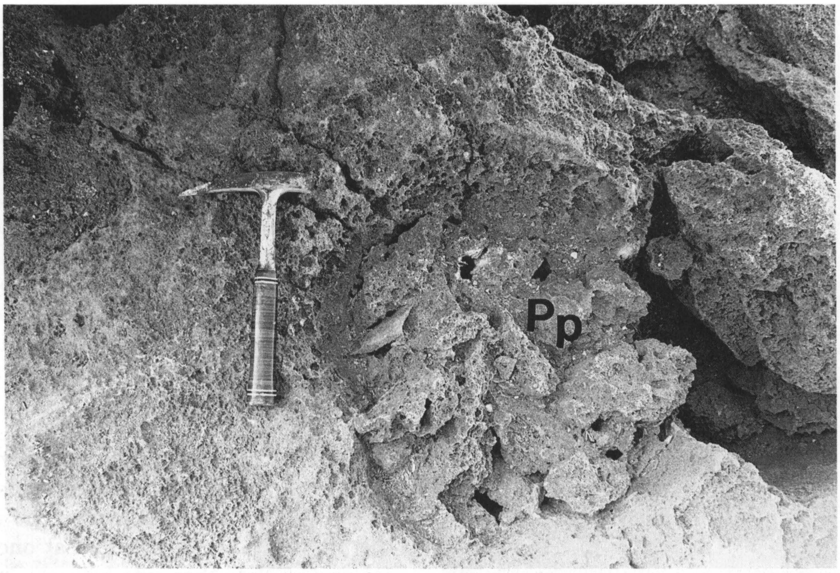

Plate 9. Palaeo-pothole fill plug (Pp) on an emergent platform at Black Rock, Zululand. Note the presence of large shell fragments and small pebbles which are commonly found in modern potholes within the intertidal zone.

er sections). Other features that can indicate the existence of an emergent platform include emergent notches and palaeo-pothole fill plugs. Palaeo-pothole fill is often preserved as plugs in circular depressions which represent pothole remnants (see Plate 9). These features are ideal sites for solution pipe development, which are deepened below the palaeo-pothole fill plug that

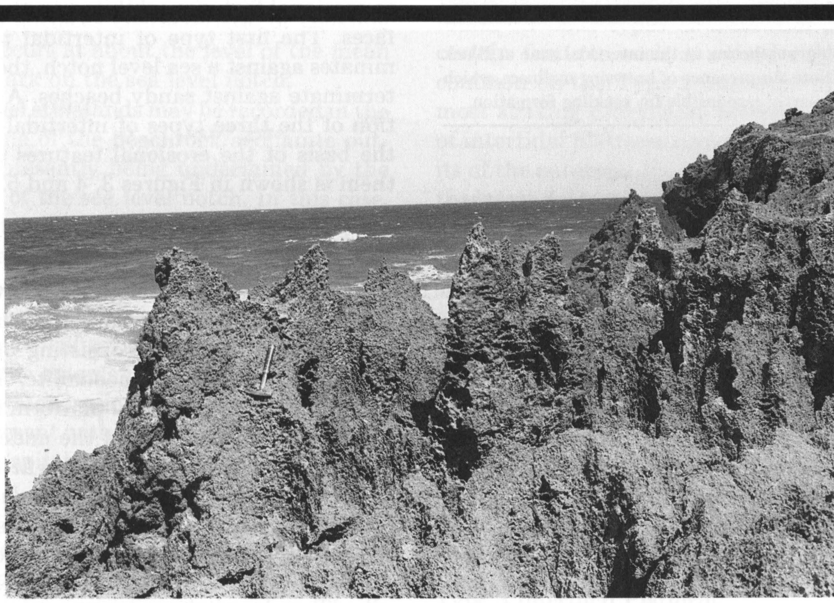

Plate 10. Spitzkarren at Black Rock, Zululand. Note the highly irregular surfaces of these features due to cockling weathering.

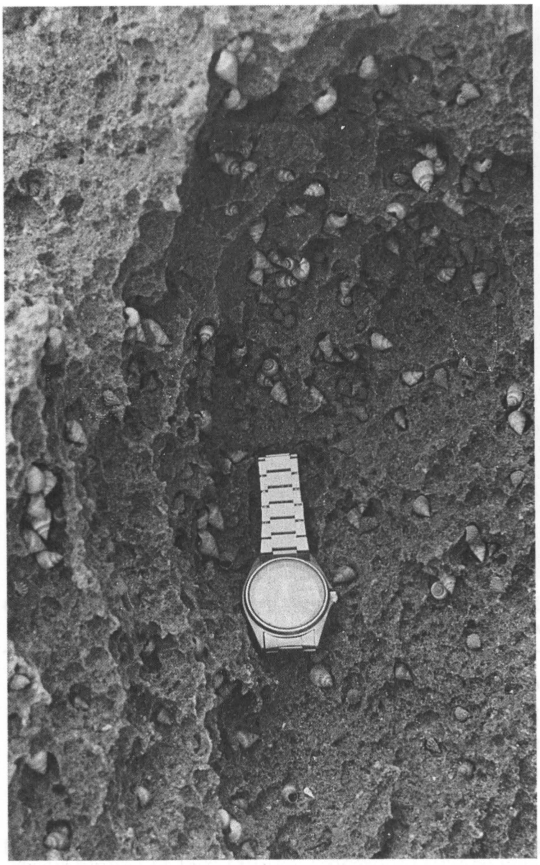

Plate 11. Cockling weathering in the intertidal zone at Black Rock, Zululand. Note the presence of browsing molluscs, which are thought to be partly responsible for cockling formation.

remains *in situ* in the aperture at the top of the developing solution pipe (see Figure 3.1).

Spitzkarren

Spizkarren are upward-pointing pyramid or projectile-shaped bodies of rock separated by clefts or solution basins (ALLEN, 1984). The distribution of these features in coastal outcrops is restricted to the supratidal environment in headlands consisting of carbonate sediments (ALLEN, 1984). Spitzkarren exhibit cockling weathering which gives the surface of these features a jagged appearance (see Figure 3.3 and Plate 10). Spitzkarren represent remnants of an earlier land surface which has been incised by chemical weathering during the formation solution basins and modified by rainwater-induced solution.

Cockling

This is a variety of Karren weathering that occurs in the supratidal environment where the rock is not subjected to prolonged streams of water but rather repeatedly wetted by wave spray, rain splash or mist (ALLEN, 1984). These structures are equidimensional to slightly elongated cup-like pits which intersect along a knife-edge (ALLEN, 1984). Individual cups rarely exceed 30 mm in diameter or 20 mm in depth and are often inhabited by browsing molluscs (see Plate 11). Cockling forms due to a combination of bioerosion and chemical induced solution by rainwater. Cockling gives rock surfaces a very pitted and irregular appearance.

Intertidal Platforms

Intertidal platforms are essentially near-flat exposures of carbonate-cemented sandstone located at the mean low water mark. The exposures of the platforms are terminated at one side by the sea and at the other side by a sea level notch or unconsolidated beach sand. Intertidal platforms form due to the landward retreat of sea level notches under attack by a combination of chemical, mechanical and biological erosion, or by exposure of buried beachrock which underwent diagenesis during a previous sea level still stand.

Three types of intertidal platform were identified in the study areas, these differ with respect to erosional features exhibited on the planed surfaces. The first type of intertidal platform terminates against a sea level notch, the other types terminate against sandy beaches. A rough zonation of the three types of intertidal platform on the basis of the erosional features exhibited on them is shown in Figures 3, 4 and 5.

Type 1 Intertidal Platform

Type 1 intertidal platforms as shown in Figure 3 and Plate 12 form by the retreat of a sea level notch into a headland consisting of carbonate-cemented beachrock or aeolianite. The seaward extremity of the intertidal platform is characterised by the development of the undercut and armoured rim. Marine algae such as *Lithothamnion* and epifauna such as barnacles (*Balanus* sp.) and oysters (*Saccostrea cuccullata*) are abundant on this part of the intertidal platform; however, populations of these organisms thin landward. Raised ridges, raised rims, terraced pools, potholes, and solution basins occupy the area landward of the armoured rim. These erosional features eventu-

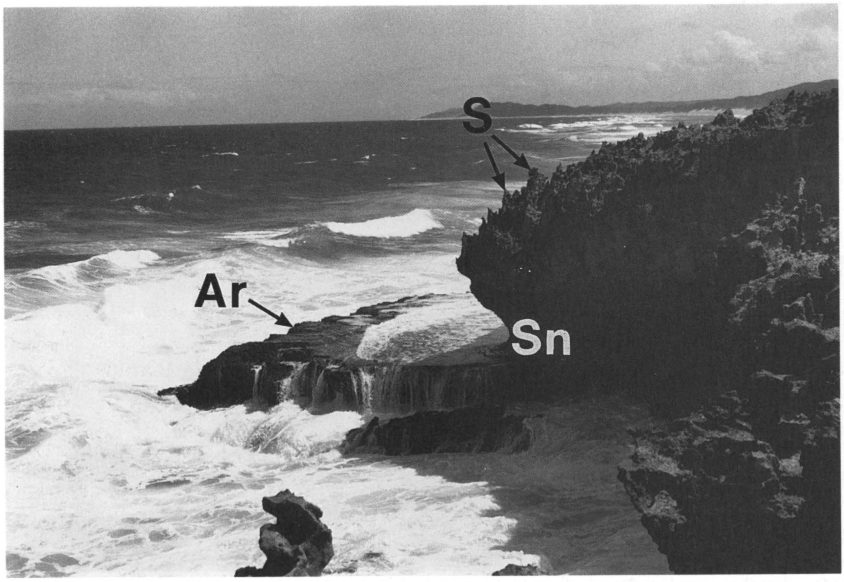

Plate 12. Type 1 intertidal platform at Black Rock showing a sea level notch (Sn), armoured rim (Ar) and spitzkarren (S).

ally thin landwards and are replaced by a flat featureless section of rock at the foot of the sea level notch. Unconsolidated sediment is uncommon on this type of intertidal platform with the exception of sediments trapped in potholes. A gradual transition from smooth rock surfaces to highly pitted surfaces characteristic of cockling weathering occurs at about the level of the mean high water mark on the sea level notch.

Past sea level stillstands may be recorded in the supratidal zone of the beachrock/aeolianite outcrop that is presently being undermined by the development of the sea level notch. In this case, erosional features such as emergent notches, solution pipes and palaeo-pothole fill plugs may be present. The degree of preservation of some of these features such as the emergent notches and palaeo-pothole fill plugs will depend on the length of time that the emergent platform has been exposed to rainwater erosion. Erosional features that are always present within the supratidal environment include spitzkarren and cockling.

Type 2 Intertidal Platform

Type 2 intertidal platform as shown in Figure 4 differs from the Type 1 variety due to the fact that it terminates against sandy beaches. The lithologies that have been planed to form this type of intertidal platform can include beachrock, aeolianite or combinations thereof. The Type 2 intertidal platform is generally wider than the previous type of intertidal platform, but the distribution of erosional features on the seaward margins of the intertidal outcrops is essentially the same. The same suite of erosional features is found on both types of intertidal platform but certain features such as raised ridges are more common on the Type 2 intertidal platform. The most striking differences between the two types of intertidal platform occur on the landward limits of the outcrops. Under fairweather conditions, the intertidal platform/sand interface is stable and it is in this proximity that rillenkarren, rill marks and shallow scoured potholes are formed. Under storm conditions when the beach is being actively eroded, large amounts of unconsolidated sediment may be stripped from the underlying beachrock/aeolianite to expose a flat featureless surface. This surface exhibits no erosional features except for the characteristic pavement of cracks that form due to undermining. During an erosive phase, the intertidal platform/sand interface can shift up to 40 m landwards (RAMSAY, *personal communication,* 1992).

Type 3 Intertidal Platform

Type 3 intertidal platform as shown in Figure 5 is characterised by distinct sedimentary bedding

Plate 13. Lingoid ridge (Lr) developed on a Type 3 intertidal platform. Note the presence of lunate megaripples (Lm) in the longshore runnel that indicate a coast parallel palaeocurrent direction.

with individual layers dipping seaward at angles ranging from 1 to 5 degrees and varying in thickness from 20 to 80 cm. The Type 3 intertidal platform has a very low profile and abuts against wide sandy beaches with very gently sloping profiles. The proximity to large quantities of mobile, unconsolidated beach-sand and the characteristic low profile of this type of intertidal platform results in a highly variable degree of exposure of the landward extremities of the intertidal platform. Only a narrow portion of the seaward part of the intertidal platform supports algal growth and it is in this vicinity that most of the erosional features are found. The armoured rim is least well developed in the laminated beachrock exposures and in many places is absent altogether. The undercut is equally well-developed as in other types of intertidal platform, though blowholes are very rare. Raised ridges are also rare on this type of intertidal platform and raised rims are completely absent. Erosional features such as solution basins and potholes are common but are restricted mainly to the seaward extremity of the intertidal platform that supports algal growth.

As algal growth thins landward so does the abundance of solution basins and potholes. These features are replaced by shallow scoured potholes that are sparsely scattered on a smooth rock surface that exhibits severe cracking. The linguoid ridge is developed on the landward side of this barren expanse of rock. Erosive processes cause the ridge to advance seaward and form a longshore runnel as it does so. The longshore runnel can represent a purely erosional phenomenon (Figure 5B) or an erosive enhancement of a lithified palaeo-ridge and runnel system (Figure 5A). Since this part of the intertidal platform represents the area of lowest relief, water and sediment become trapped between the linguoid ridge and the beach. Consequently, very strong sediment-carrying currents are generated here during incoming and outgoing tides. It is not uncommon for more than one linguoid ridge to develop on the same intertidal platform. In this instance, the intertidal platform takes on a stepped appearance and consequently displays more relief. The linguoid ridge on the landward extremity of the intertidal platform generally displays the greatest relief and the longshore runnel landward of this feature is the most active.

Sediment migrates in the runnel features as lunate megaripples in a longshore direction and as oscillation or current ripples in a coast normal direction (see Plate 13). During periods of beach erosion, the longshore runnels act as sediment conduits whereby sediment is stripped from the

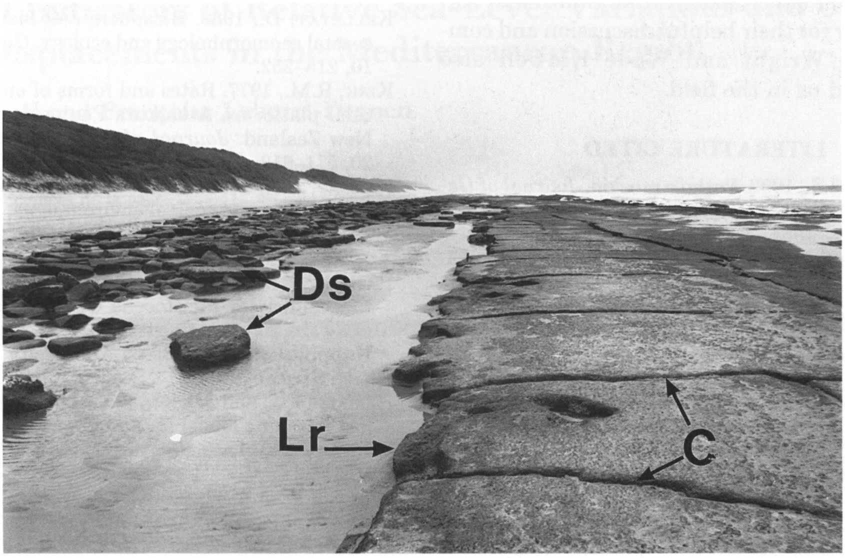

Plate 14. Type 3 intertidal platform showing a linguoid ridge (Lr) and multiple cracks (C) due to undermining. Note the presence of numerous disrupted slabs (Ds) in the longshore runnel.

beach along the runnel feature and transported by rip currents to build offshore bars. During periods of coastal accretion, sediment from the offshore bars is transported onshore, and the longshore runnels act as sediment traps.

Rillenkarren and shallow scoured potholes are the only erosional features exhibited in the lithified substrate of the runnel feature. These features are often encountered at the fairweather beach/runnel interface where rill marks develop. Slabs of laminated beachrock are often encountered in a haphazard arrangement protruding from under a thin cover of beach sand landwards of the runnel or in the longshore runnel itself (see Plate 14). These disrupted slabs are deposited here due to undermining of beachrock at higher levels, by undermining of the linguoid ridge, or by collapsed slabs on the seaward extremity of the intertidal platform being thrown up the beach during storm conditions.

CONCLUSION

The importance of chemical erosion on carbonate-cemented sediments within the marine environment has long been a contentious issue among marine geologists. By studying the erosional features themselves, it would seem that this form of erosion is underestimated within a marine context. Only a more detailed chemical investigation of this phenomenon will provide the necessary answers to this ongoing debate.

With regard to the erosional features described in this paper, it is obvious that although many previous workers have described or illustrated them, there is a lack of consensus in terminology. We hope that this paper will help overcome this problem, as well as provide a basis for comparison of erosional features in beachrocks and coastal aeolianites elsewhere in the world.

Recognition of the erosional features within the supratidal environment as well as below present sea level can provide valuable information concerning previous sea level stillstands. Attaining an understanding of this suite of erosional features and a knowledge of the spatial distribution of the erosional phenomenon within the intertidal and supratidal zones will thus provide a powerful tool for coastal evolution studies.

ACKNOWLEDGEMENTS

WRM acknowledges the permission of the Chief Director of the Geological Survey to publish this work. TRM acknowledges support for field work by the University of Natal Research Fund, and we both thank Natal Parks Board and the Kwazulu Bureau of Natural Resources for their help in the field. We are especially grateful to our colleagues, Drs. Peter Ramsay, Alan Smith and Andrew Cooper for their helpful discussion and comments. Ian Wright and Wade Kidwell also accompanied us in the field.

LITERATURE CITED

ALEXANDER, H.S., 1932. Pothole erosion. *Journal of Geology*, 40, 305–307.

ALLEN, J.R.L., 1984. *Sedimentary Structures: Their Character and Physical Basis*. Vol. 1. New York: Elsevier, pp. 223–265.

BOWIE, D.K., 1966. The Marine Geology of False Bay. Unpublished M.Sc. Thesis, University of Cape Town, South Africa.

COETZEE, F., 1975a. Coastal aeolianites at Black Rock, Northern Zululand. *Transactions of the Geological Society of South Africa*, 78, 313–322.

COETZEE, F., 1975b. Solution pipes in coastal aeolianites of Zululand And Mozambique. *Transactions of the Geological Society of South Africa*, 78, 323–333.

COOPER, J.A.G., 1991a. Shoreline deposits and diagenesis resulting from two late Pleistocene highstands near +5 and +6 metres, Durban, South Africa. *Marine Geology*, 97, 325–343.

COOPER, J.A.G., 1991b. Beachrock formation in low latitudes: Implications for coastal evolutionary models. *Marine Geology*, 98, 145–154.

EMERY, D.O., 1946. Marine solution basins. *Journal of Geology*, 54, 209–228.

FAIRBRIDGE, R.W., 1948. Notes on the geomorphology of the Pelsart Group of the Houtman's Abrolhos I stands. *Joint Royal Society of Western Australia*, 33, 1–43.

FAIRBRIDGE, R.W., 1950. The geology and geomorphology of Point Peron, Western Australia. *Journal of the Royal Society of Western Australia*, 34, 35–72.

GUILCHER, A., 1988. *Coral Reef Geomorphology*. New York: Wiley, pp. 12–40.

KAYE, C.A., 1957. The effect of solvent motion on limestone solution. *Journal of Geology*, 65, 35–46.

KELLETAT, D., 1989. Biosphere and man as agents in coastal geomorphology and ecology. *Geookodynamik*, 10, 215–252.

KIRK, R.M., 1977. Rates and forms of erosion on intertidal platforms, Atkaikura Peninsula, South Island, New Zealand. *Journal of Geology and Geophysics*, 20, 571–613.

RAMSAY, P.J., 1990. A new method for reconstructing late Pleistocene coastal environments, Sodwana Bay, Zululand. *South African Geological Survey Report, 1990-0227*, pp. 1–44.

RAMSAY, P.J., 1991. Sedimentology, Coral Reef Zonation, and Late Pleistocene Coastline Models of the Sodwana Bay Continental Shelf, Northern Zululand. Unpublished PhD. Thesis, University of Natal, Durban, South Africa.

RAMSAY, P.J. and MASON, T.R., 1990. Development of a type zoning model for Zululand coral reef, Sodwana Bay, South Africa. *Journal of Coastal Research*, 6(4), 829–852.

RILEY, J.P. and SKIRROW, G., 1965. *Chemical Oceanography*. London: Academic, pp. 127–292.

RUSSELL, R.J. and MCINTIRE, W.G., 1965. Southern hemisphere beach rock. *Geographical Review*, 55, 17–45.

SCHEER, G., 1971. Coral reefs and coral genera in the Red Sea and Indian Ocean. *Symposium of the Zoological Society of London*, 28, 329–367.

SIESSER, W.G., 1974. Relict and recent beachrock from South Africa. *Geological Society of America Bulletin*, 85, 1849–1854.

TINLEY, K.L., 1987. Coastal dunes of South Africa. *South African National Scientific Programmes*. Report number 109, pp. 1–300.

VITA-FINZI, C. and CORNELIUS, P.F.S., 1973. Cliff sapping by molluscs in Oman. *Journal of Sedimentary Petrology*, 43, 30–32.