Beach Rock Ridges/Bands along a High-Energy Coast in Southwestern Australia—Their Significance and Use in Coastal History

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ABSTRACT


INTRODUCTION

Beach rock, i.e. indurated beach sediment, has been documented from a considerable range of tropical and subtropical beach environments (BRICKER, 1971; SCHOLTEN, 1971). Much of the literature is concerned with its origin (KUENEN, 1933; GINSBURG, 1953; MAXWELL, 1962; DAVIES and KINSEY, 1973; HANOR, 1978; HOPLEY and MACKAY, 1978; MOORE and BILLINGS, 1971), its age and rate of formation (FRANKEL, 1968; TACHIBANA and SAKAGUCHI, 1971), the type of cementing agents (KNOX, 1974; FOLK, 1974; TAYLOR and ULLINGS, 1971; MOORE, 1971; TIETZ and MULLER, 1971) and its use as a sea level indicator (LOVELL, 1975; STEARNS, 1974; STEARNS, 1974; SIESSER, 1974; RUSSELL, 1959).

Beach rock is developing under the beach of a retreating barrier in southwestern Australia and is exhumed as the coast erodes. As the barrier retreats, the underlying estuarine sediments are exposed, and exhumed beach rock is left as residuals on the submarine shelf. Consequently, it develops a definitive small scale geomorphic unit that reflects its mode of formation and the subsequent coastal history. The resultant geomorphic unit consists of submerged shore-parallel ridges, bands and linear slabs of beach rock separated by ribbons of sand. The usefulness of the beach rock residuals is that they record marked coastal retreat over a relatively short period of the late Holocene. Their configuration provides information about the dynamic nature of a retreating shore and allows a reconstruction of geomorphic history.

ADDITIONAL INDEX WORDS: Beach rock, coastal erosion, Holocene coastal history, southwestern Australian coast.

REGIONAL AND GEOLOGICAL SETTING

Coastal Plain

The study area is the exposed shore of Leschenault Peninsula, a barrier dune system located in subtropical, southwestern Australia (Figure 1). The coastal lowlands (the Swan Coastal Plain) of this part of Western Australia are composed of dunes,
**Figure 2**

- **A**
  - Phanerozoic sediment
  - Precambrian rock

- **B**
  - Safety Bay Sand

- **C**
  - Indian Ocean
  - Safety Bay Sand

- **D**
  - Swan Coastal Plain
  - Yilgarn Block

- **E**
  - Holocene: Safety Bay Sand
  - Various Pleistocene formations
  - Precambrian rock

**Legend**

- Holocene: Safety Bay Sand
- Various Pleistocene formations
- Precambrian rock

**Key**

- Erosion on seaward face of barrier
- Barrier dune system
- Parabolic dune blowouts encroaching into the estuarine lagoon
- Estuarine lagoon

**Stratigraphy**

- Exposed Pleistocene limestone
- Exposed estuarine sediment

**Temporal Periods**

- **Holocene**
  - Aeolian and beach sand (Safety Bay Sand)
  - Estuarine/lagoonal sediment (Leschenault Formation)

- **Pleistocene**
  - Quartz sand
  - Limestone
Beach Rock Ridges/Bands in S W Australia

fluvial deposits, estuarine units, wetlands and strandline deposits that form the Quaternary portion of the Phanerozoic Perth Basin (JUTSON, 1949; MCAARTHUR and BETTENAY, 1960; SEDDON, 1972; PLAYFORD et al., 1976). The youngest coastal deposit on the Swan Coastal Plain is the Safety Bay Sand, a formation that occurs discontinuously as Holocene beach/dune sequences along the shore (PASSMORE, 1970; PLAYFORD et al., 1976; SEMENIUK and SEARLE, 1985).

Stratigraphy

The main stratigraphic units in the area relevant to this study are (Figure 1): Safety Bay Sand (Holocene), Leschenault Formation (Holocene), and Tamala Limestone (Pleistocene). The Safety Bay Sand comprises the barrier dunes (Figure 1) that protect a lagoon with estuarine deposits (Leschenault Formation). The Holocene history of this coast is described in SEMENIUK (1983, 1985); a brief summary is presented below.

Stratigraphic relationships and radiocarbon ages indicate that the Holocene sediments were emplaced in three principal stages. Stage 1, with sea level 2-3 m below present, involved development and retreat of barrier dunes and deposition of estuarine sediments. Stage 2 with sea level 3-4 m above present resulted in coastal progradation on the west side of the barrier to develop a shoaling sequence of subtidal, beach, beachridge and dune units. Stage 3 is the present dynamic situation and again involves barrier retreat, further accumulation of estuarine sediment, and development of beach rock.

Meteorology/Oceanography

The summer and winter patterns of meteorology and oceanography in this region are distinct and are related to the eastward-travelling high/low pressure systems (GENTILLI, 1972; SEMENIUK and MEagher, 1981; STEEDMAN and CRAIG, 1983). Winter is characterized by storms with intervening relative calms. During storms wind has mean speeds up to 20 m/s for 6-24 hour duration, and mainly prevails from the northwest, west and southwest. Two to four such storms may be expected each winter, with minor storms occurring approximately every two weeks. Major storms occur approximately every (5-)10-20 years. During summer, seabreeze/land-breeze systems control the winds in the coastal area; seabreezes with speeds up to 15 m/s originate from the west to southwest. In summer there also is the possibility of infrequent tropical cyclones reaching the area; although they are weakening, these storms are still capable of significant coastal erosion (SEmeniuk and MEaGHER, 1981).

Important factors in beach erosion are tide and storm-surge levels. This region is microtidal (Hodgkin and Di LolLO, 1957; AUSTRALIAN NATIONAL TIDE TABLES, 1985), but MSL is influenced markedly by barometric pressure. During storms, low barometric pressure together with wind stress on the sea toward the coast, combine to result in wave attack high up the beach.

The Leschenault Peninsula faces the Indian Ocean and there are no other barriers or reefs offshore. Waves impinging on the coast are a combination of wind waves and swell. Wind waves emanate from west and southwest; swell also is predominantly from west and southwest. In combination wind waves and swell result in net erosion and a net northward littoral drift. This pattern is reversed during periodic storms that emanate from the northwest.

Geomorphic Processes

Erosion is the process most important to the development of Holocene geomorphology on the exposed portion of the barrier. The influence of erosion on coastal morphology is direct: (1) the western shoreface is cliffed with exposure of living tree roots and internal dune features (soils, large-scale cross laminae and cross bedding, and cemented zones such as groundwater calcrete); and (2) surficial sediments periodically are stripped and older stratigraphic units along the shoreface are exposed.

Two types of erosion are evident, wave erosion and wind erosion. Wave erosion is more important. The foreshore along the barrier changes seasonally from a full summer beach to a depleted winter beach and seasonally there is minor net retreat. Calcrete and soils that crop out on the shoreface are also exposed seasonally and may be eroded by...
up to 1-2 m. Periodically major storms and cyclones result in more severe erosion. In 1978, for instance, the coast retreated locally up to 30 m during the storms associated with Cyclone Alby (SEmeniuk and Meagher, 1981). Storms exhume large expanses of groundwater calcrite, truncate soils, and truncate beachridge debris which has been deposited in the preceding decades (see Figure 7 of Semeniuk and Meagher, 1981). Aerial photographs between 1941 and 1983 corroborate these observations and show an overall net erosion of the coast in the past 42 years. Wind erosion of the exposed face of the barrier continually exposes roots of living plants and develops deflation lags of cemented materials. The effect of wind is relatively slow, but the result is still a net erosion. In summary, coastal retreat is proceeding consistently and slowly by wind erosion, more moderately by seasonal winter storms, and rapidly but sporadically by periodic large storms and cyclones.

Earlier studies of coastal erosion in this area have been undertaken by Semeniuk and Meagher.
SEMENIUK and MEAGHER determined erosional rates of up to 1-2 m/yr. Their short-term studies between 1976 and 1979, however, were undertaken during a period of extreme storms and cyclones; their long-term analysis used aerial photographs between 1941 and 1971. The PUBLIC WORKS DEPARTMENT (1983) produced maps by photogrammetry using aerial photographs taken between 1955 and 1982. Analysis of these maps at 18 transects along a 10 km stretch of coast shows net erosion along the coast but variable rates of erosion spatially along the coast. The mean retreat rate is $0.5 \pm 0.4$ m/yr. Overall both studies indicate net

![Photograph A](image1)

![Photograph B](image2)

Figure 3. Photographs of beach rock slabbed to illustrate sedimentary features. (A) Laminated beach rock with upper surface bored by lithophagous bivalves. (B) Cross-bedded gravelly beach rock.
retreat but with a variable retreat rate from 0.5–1.0 m/yr.

Extrapolation would suggest that, even with the use of the lower erosional rates, an extraordinary width of at least 500 m of coast has been lost every 1,000 years. It appears that erosion has been dominant in the late Holocene for this area since sea level reached its present position some 3,000 years ago (SEMENIUK, 1983, 1985). The evidence of exhumed stratigraphic units also indicates that erosion has been a long-term process of the late Holocene rather than a short-term event.

As the coast retreats it exposes recently formed beach rock and this retreat is clearly reflected in the parallel bands of beach rock that occur up to 1000 m offshore. The beach rock forms the submarine ridge system of the shelf as described in the next section.

DESCRIPTION OF BEACH ROCK

Geomorphic Occurrence

The submarine shelf immediately offshore from the beach face of the barrier system is gently sloping and extends from low water to over 20 m depth. Most of the sea floor consists of Pleistocene limestone which forms a generally hard basement to the unconsolidated Holocene units (Figure 1). The submarine topography of this limestone varies mainly from a flat pavement to a rugged reef.

In an elongate zone parallel to the shore between low water and 6 m depth, and up to 1000 m offshore, the shelf is dominated by ridges, strips and linear slabs of beach rock (Figure 2). There are also strip outcrops of estuarine mud and other small outcrops of cemented residuals such as estuarine shelly sand (cemented in the phreatic zone beneath the barrier dunes but now exhumed and exposed in the submarine environment). Beach rock residuals, however, are clearly discernable from the other materials as laminated and cross-laminated limestone containing beach shell.

The ridges and linear slabs of beach rock, 1 to 4 m thick, are 30–150 m apart, and are subparallel to shore. Marine erosion and the bedding lamination have resulted in a craggy terraced morphology. Sand locally veneers these ridges and forms shallow accumulations in inter-ridge depressions.

Description

The beach rock is an indurated sand, gravelly sand or shelly sand similar to modern beach sediments onshore (Figure 3). The sequence of sediment types within the beach rock forms an incomplete beach sequence as described by SEMENIUK and JOHNSON (1982). Only the lower two facies of the normally threefold beach sequence are present (i.e. subtidal trough-bedded sands, shelly sands, and lithoclastic gravelly sands, overlain by swash zone laminated sand and shelly sand).

The beach rock is cemented by short rhomboidal/stumpy crystals of magnesian calcite c. 1 μm in size. Microprobe analyses of 8 samples showed a content of 4.0 ± 1.0 mol % Mg, and no Sr. In contrast, both the Pleistocene limestone and the indurated dune sands of the barrier are cemented by low-magnesium sparry calcite and calcrete. The beach-rock cementation is quite apparent in the submarine environment and in patches in the phreatic zone under the beach face where the stratigraphic sequence of beach facies are cemented in situ. The cementation occurs in a zone up to 4 m thick, but the zone of most marked cementation is generally less than 1 m thick, thus forming a slab-like induration zone.

Whilst residuals of former intertidal beach rock remain in offshore strandlines, and cementation is present beneath the present beach, the zone of induration is not traceable to any extent under the barrier inwards of the shoreface (Figure 4). Apparently the induration is taking place where marine water and outflowing freshwater mix, and is similar to beach rock formation described from tropical regions (BRICKER, 1971; HANOR, 1978).

Processes of Exhumation

Beach rock is exhumed from under the beach face by coastal retreat. Slow coastal erosion (<0.5 m/year) results in the development of a broad ribbon of beach rock parallel to the coast, and if such erosion were to continue uninterrupted then a sheet of beach rock would be left because the generation and exposure of beach rock would keep pace with rates of erosion. However, infrequent large storms that cause rapid and marked coastal retreat (c. 30 m) for short periods (c. 1–2 days), interspersed with periods of normal prevailing conditions of slow erosion, will produce parallel bands of beach rock. The bands of beach rock are thus the product of cementation where a beach is slowly eroding; the intervening areas represent.
Beach Rock Ridges/Bands in SW Australia

A

West

Sea level

Indian Ocean

Leschenault Inlet

Enlargement. See B below

Holocene aeolian sand: Safety Bay Sand

Holocene estuarine sediment: Leschenault Formation

Pleistocene limestone

100 m

10 m

B

Beach rock, although now residual in the offshore-nearshore, is not traceable at all into the barrier dunes

Sea level

Beach rock in situ under beach face

Submerged slabs of beach rock

Stratigraphic study site

Trench site

Aeolian and beach sediment: Safety Bay Sand

Estuarine sediment: Leschenault Formation

Pleistocene quartz sand

Pleistocene limestone

500 m

5 m
periods of very rapid coastal retreat. It seems that intermittent coastal erosion in its wake leaves ridges, strips, linear slabs and sheets of beach rock.

Once exhumed, slabs of beach rock undergo wave attack and degradation. All stages of beach rock exhumation, reworking and disintegration are evident along the nearshore area adjacent to the barrier system. Beach rock is readily reworked because it is imbedded in un cemented host sand. Wave attack results in undercutting and shifting of sand in such a way so that gradually the beach rock slab settles onto topographically lower portions of the shore face. The process of settling down is terminated when the slab finally comes to rest on the underlying Pleistocene limestone pavement or exposed estuarine sediment (Figure 5).

The beach rock degrades (disintegrates) mainly by biological processes (cf. McLEAN, 1967, 1974). Its surface is rapidly colonised by algae, grazing mollusces, echinoderms and lithophagic organisms (Figure 3). As a result the surface is bored, honeycombed and generally degraded. Near the shore young beach rock is generally of marked relief and relatively more continuous along its strike length. Disintegrated and degraded beach rock residuals are more common offshore.

**Age of Beach Rock Ridges/Bands**

Since the bands and linear slabs of beach rock are residuals left as the coast retreats, it is assumed that the oldest would be farthest seaward and the youngest would be either still forming beneath the beach face or lodged in the inshore zone. Thus the parallel array of ridges or bands would represent isochrons providing a relative chronology for coastal retreat, and would also provide an indication of the periodicity of major storms that caused the marked retreat.

It is not possible, however, to easily date the beach rock of the Leschenault Peninsula by radiocarbon using mollusc shell. This is because the shells that are incorporated into modern beaches and thus the beach rock have the following sources: (1) modern nearshore benthos (of which Donax is most abundant); (2) reworked relict shells (c. 4,800-3,600 14C yrs) from stranded relict beach deposits deposited during stage 2 of the history of the barrier; Donax, Donacilla and Glycymeris are common and frequently have adhering CaCO3 cement (calcrete or spar-cemented nodules); (3) reworked shells (c. 7,000 years BP) from exhumed estuarine molluscs (for faunal list see SEMENIUK, 1983); (4) reworked shells from Pleistocene limestone.

The order of abundance of these shells are: modern shells = relict beach shells > estuarine shells > Pleistocene shells.

If these molluscs were bulk analyzed, the age determinations would be meaningless. Even ages from selected distinct species (e.g., Donax) would provide erroneous results because second-cycle shells reworked from the Stage 2 depositional unit some 3,600-4,800 14C yrs BP are indistinguishable in many instances from modern shells.

The beach rock slabs in the nearshore to offshore environment rest on exhumed estuarine sediment containing shell dated at 7,765-7,890 14C yrs BP. This at least indicates a Holocene age for the beach rock, but because a disconformity separates the slabs and the estuarine sediment the dates cannot be used to deduce the age of the beach rock. Until the magnesium calcite cement of the beach rock itself is processed for radiocarbon the age of the beach rock will have to be determined from gross stratigraphic relationships and other data on age structure and history of the barrier.

The Holocene history of the area described earlier in this paper suggests that the barrier was emplaced in 3 stages. Each of these stages has been dated (SEmeniuk, 1985) and potentially could be of use in deducting the age of beach rock in the area. The first stage involving a retreating barrier cannot be considered because sediments deposited at this time have since been eroded and reburied by sediment of Stage 2. The sequence of Stage 2 also is out of the question for dating the beach rock because this stage involved net coastal progradation and not erosion. The third stage in the development of the coastal barrier is the current phase that began about 2,800 14C yrs BP with reactivated erosion on the exposed face of the barrier which is associated with renewed mobilisation of parabolic dunes across the barrier into the protected estuarine lagoon. The date of 2,800 14C yr records the reactivation of erosional conditions leading up to the present day, and thus records the maximum possible age of the most seaward beach rock.

Given the modern rates of bioerosion and physical degradation it is unlikely, however that the most seaward occurrence of beach rock is as old as 2,800 14C yr. The rates of erosion of the coast determined by shoreline monitoring over the past 10 years and

Figure 4 (preceding page): Transect from nearshore to onshore showing stratigraphic distribution of beach rock. Beach rock is not traceable to landward beyond the backshore.
Beach rock developed near interface between marine and fresh water zones.

Coastal retreat

Residual beach rock stranded by coastal retreat

Migration of groundwater fields as coast retreats

determined by photogrammetric analysis over 40 years of aerial photography are in the order of 0.5-1.0 m/yr. Accordingly the most seaward occurrence of beach rock now located some 1,000 m offshore would be in the order of 1.000-2,000 years old. Thus the most seaward portion of the residual beach rocks some 1,000 m offshore are interpreted to be most likely 1,000-2,000 years old, but possibly up to 2,800 yrs old. Beach rock has been observed in the phreatic zone under the backshore of beaches that have formed only in the last 40 yrs and therefore the youngest age of the most shoreward occurrence of beach rock is contemporary.

DISCUSSION

The results presented here lead to several conclusions, firstly concerning the development of nearshore rocky reefs and ridges and geomorphic units of any age (Quaternary, Tertiary, etc.), secondly on the significance of linear slabs and bars of beach rock, and thirdly on the usefulness of linear beach rock trends in reconstructing coastal history.

It is evident that nearshore and offshore rocky reefs and residual carbonate-cemented rock pavements and slabs can be developed under a combination of shoreline processes that include beach rock formation in the phreatic zone of a beach, followed by coastal erosion (cf. HATTIN and DODD, 1978; COORAY, 1968; RUSSELL, 1959). This process provides coastal sedimentologists and geomorphologists with explanations for the occurrence of submerged nearshore rocky slabs and submarine residuals of cemented rock that need not represent abandoned beach rock shorelines developed by a rising sea level.

Slow coastal erosion concomitant with phreatic cementation which has enough time to develop indurated horizons under the retreating beach face will result in a broad zone or sheet of beach rock. The width of the zone will be determined by the rate of erosion keeping pace with beach-rock cementation and by the interval of this prolonged slow erosion. Coastal erosion of 0.5 m/yr for 100 years, for instance, could develop a beach rock ribbon or zone (albeit fractured and disrupted) some 50 m wide. However, parallel bands of beach rock separated by beach-rock-free zones indicate that coastal retreat is occurring by a process of slow erosion punctuated by rapid erosion through periodic large storms. Slow erosion of 0.5 m/yr interspersed with a rapid rate of erosion of 50 m, say every 50 years, would result in parallel bands of beach rock perhaps some 25 m wide separated by beach-rock-free zones some 50 m wide. The width and spacing of bands of beach rock when used in conjunction with known prevailing rates of slow coastal erosion, give an indication of the history of coastal erosion. The model of periodic large-scale storm-induced erosion alternating with prevailing slow erosion that results in the development of linear beach rock trends therefore is useful for reconstructing geomorphic history along high energy, beach-rock lined coasts.

Beach rock indicates the former occurrence of a specific linear environment—i.e., the shoreline and the interaction of freshwater and seawater in the phreatic zone under the beach face (Figure 5). Once it is exhumed and left as an isolated residual it can then delineate former shorelines. Unconsolidated coastal sands on the other hand once eroded from the shoreline can be removed from the immediate coastal area, or can be imprinted by different processes in their new site of emplacement, or can be reworked, or stranded elsewhere. Such coastal sands thus may offer little or no information about former coastal history. On the other hand, beach rock is relatively resistant and can be viewed as a long-term residual product and a useful record of shore position. Beach rock has been used in this manner by ULZEGA et al. (1986), SIESSER (1974), STEARNS (1974) and others for the identification of Pleistocene and early Holocene shorelines.

Beach-rock ridges/bands up to 1,000 m offshore in the Leschenault area indicate the position of the strandline to have been at least 1,000 m farther seaward earlier in the Holocene. However, the usefulness of the beach-rock residuals in this area is that they record marked coastal retreat over a relatively short period of the Holocene and indicate by their configuration and distribution the varying rates of coastal retreat. As such the beach rock residuals now submerged offshore provide an additional indicator of the history and extent of retreat of a retrograding barrier. The width and spacing of the submerged beach rock zone also indicates differential retreat along the Leschenault Peninsula barrier. To the north the retreat has occurred over 500 m or less, to the south retreat has occurred over 1,000 m, indicating that erosion has been consistently of a greater magnitude along southern parts of the barrier.
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ZUSAMMENFASSUNG