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Rapid beachrock cementation on a South African beach: Linking morphodynamics and cement style

E.Wiles, A.N. Green, J.A.G. Cooper

Abstract

Rapid cementation (b5 years) of beachrock is reported fromthewave-dominated, microtidal coastline ofDurban, South Africa. The beachrock is developing at mean sea level on a steep (10°–30°), reflective beach prone to periodic erosion by high-energy wave action; the most recent erosional event resulted in retrogradation of the beach by up to 10 m landward of the beachrock outcrop discussed in this study. Transmitted light microscopy and scanning electron micrographs show the precipitation of two dominant cement types which are linked to the beachface morphodynamics. During the accreted beach phase, when the locus of beachrock formation lay well landward of the beachface in the undersaturated upper intertidal to supra tidal backbeach, meniscus cements were precipitated. Following a period of erosion, associated with a landward shift of the beachface, the incipient beachrock was then exposed to saturated conditions which promoted growth of acicular cements. Contemporary beachrock cementation occurred very rapidly (b5 years) between significant erosional events. The observed cement textures record short-term beach progradation and retrogradation but are similar to those typically associated with longer-term regression and transgression.

Introduction

Beachrocks represent the cemented (calcitic and aragonitic cements) products of littoral and intertidal sediments (Flügel, 2004; Vousdoukas et al., 2007). Latitudes between 20°–40° host the majority of reported beachrock occurrences (Vousdoukas et al., 2007), with beachrock common to the Mediterranean and Caribbean, tropical and subtropical Atlantic, as well as the atolls of the Pacific and Indian Oceans. A few reports of high latitude beachrocks exist (e.g., Gaulin, 1984; Sellwood, 1995; Kneale and Viles, 2000; Rey et al., 2004; Cooper et al., 2017), however it is in the subtropics where beachrock is considered most common.

A key feature of beachrocks is the preservation of the original sedimentary structures and textures of the beach during the lithification process. This provides a number of clues to the depositional setting at the time of cementation (Vousdoukas et al., 2007; Kelly et al., 2014). A recent review by Mauz et al. (2015) described how beachrocks can be used as useful tools in the reconstruction of palaeo-sea levels. This is mostly due to the relatively precise framework within which beachrocks occur, specifically the location of the proto-beachrock relative to mean sea level and how this affects the style and history of cement precipitation. The changes in cement phase are often cited as evidence of changes in longer term relative sea level, as driven by changes in the relative elevation of the main phreatic/vadose mixing zones in which high Mg calcite is precipitated (Strasser et al., 1989; Mauz et al., 2015; Ozturk et al., 2016).

Cementation is affected by several factors, based on setting, and includes direct precipitation from seawater (Ginsburg, 1956), CaCO3 flux in response to mixing of marine and meteoric waters (Milliman, 1974), evaporation of groundwater in arid settings (Russell and McIntire, 1965), CO2 degassing fromdissolved CaCO3-rich groundwater (Hanor, 1978) andmicrobial activity (Neumeier, 1999). Beachrocks can form very rapidly on scales of months to years (Frankel, 1968). On the shorter term, and especially in the case of rapid cementation, the potential also exists for short-termbeach morphodynamics and its associated effects on the mixing zone to influence cement type and texture. This paper examines the formation of contemporary beachrock in this light. We consider a beachrock from the subtropical Durban coastline of SE Africa. The beachrock has formed over a very short period of time and our aim is to examine whether a link between beach morphodynamics and beachrock sedimentology and diagenesis exists.

1.1. Beachrock cements

Beachrock cements are predominantly precipitated in the mixing zone between fresh and saline waters (Vousdoukas et al., 2007). The zone of mixing is typically associated with the foreshore, between the mean low and mean high water levels. The mixing zone is chemically dynamic, comprising pore fluids fromadjacent fresh and saline environmental endmembers (Moore, 1973). The key to cementation is supersaturation of calcite in solution, followed by degassing of CO2, which results in the precipitation of calcium carbonate cement (Field, 1919; Thorstenson et al., 1972; Plummer, 1975; Meyers, 1987). Under high temperatures, less seawater is required to achieve suitable supersaturation of calcite in solution, while increased degassing of CO2 results in a higher pH and potential for rapid precipitation of calcium carbonate cement. Unconsolidated sediments close to the supersaturated source are thus likely cemented first, while zones of increased microbial activity induce preferential, rapid, cement precipitation (Neumeier, 1999).
Within this supersaturated zone, precipitation of cement may be rapid enough to outpace sedimentation, thus transforming unconsolidated sediment into beachrock, a process that can be particularly rapid; in the general study area, Cawthra and Uken (2012) reported cementation of 70 year old artefacts into beachrock.
Beachrock cement types comprise metastable carbonate phases; aragonite, and high-Mg calcite (HMC) (Vousdoukas et al., 2007). Each phase corresponds to a defined groundwater zone. Aragonite, and high-Mg calcite are associated with seawater (Stoddart and Cann, 1965; Alexandersson, 1969; Alexandersson, 1972; Alexandersson and Milliman, 1981; Calvet et al., 2003), and calcite with fresh or meteoric water (Russell, 1959, 1962, 1963; Stoddart and Cann, 1965). This association with water chemistry has strengthened the case for beachrock and its cements as effective sea-level indicator points (Mauz et al., 2015), so long as there is meaningful supporting evidence (Hopley, 1986).

Environmental setting

The east coast of South Africa is a wave-dominated (Hs = 1.8 m), upper microtidal coastline (spring tidal range 1.8 m) (Cooper, 2001; Moes and Rossouw, 2008). The average sea temperature of Durban ranges from 22°–26 °C and may reach a maximum of 28° in late summer. Glenashley Beach (Fig. 1), 13 km north of Durban, is a highenergy, reflective beach comprising a narrow backbeach, berm crest, upper and lower beach face (usually in excess of 10° and up to 30°), and a subtidal step at the base of the lower beach face. During sample collection, the upper/lower beach face and berm had been eroded during a high-energy swell event, that cut a 3 m scarp, undercut foredunes and produced a single steep beach face (10–12°) (Fig. 2a). Pronounced coastal erosion affects the east coast of South Africa in a periodic manner. Over the past two decades several significant highswell (Hs ≥4.5 m) events were recorded (Smith et al., 2007, 2010, 2013). During the most extreme phase of erosion (March 2007) the study beach was almost completely eroded to underlying bedrock (Smith et al., 2013). Subsequent erosion of the beach in 2011 caused coastal recession to a position landward of the former foredune (Smith et al., 2013), ~10 m inland of the zone of contemporary beachrock formation (Fig. 1). Since 2011 there has been net beach progradation as the beach has been rebuilt, with no further significant erosion events. The formation of today's beach and its associated beachrock therefore postdates 2011 and places the time frame of cementation within a ~5 year period.

Methods

The study area, Glenashley Beach, lies ca. 13 km north of Durban along South Africa's east coast. The foredunes are backed by a coastal road and suburban housing rather than vegetated dunes. A storm water outfall set on piles extends from the seaward toe of the foredune 20 m south east across the beach. A period of high-energy swell had eroded a significant volume of the beach undercutting the foredunes and fortuitously exposing two beachrock outcrops in the foreshore. The outcrops were only briefly exposed (45 min) during spring low tide on 3 February 2015 (Fig. 2b,c). The stratigraphic architecture of the deposit was photographed and described from encrustations on a stormwater outfallwhere the beachrock cropped out at the same elevation along coastal strike. Elevations were established relative to mean sea level (MSL) using an RTK GPS system.
Samples of beachrock were broken off from the two outcrops within the intertidal zone (ca. 0mMSL) and rinsed in seawater to remove non-cemented grains. The outcrop was covered by severalmetres of sediment over the subsequent three days. The partiallycemented samples were impregnated with resin to create a solid sample with which to work. Thin sections were prepared for analysis using transmitted light microscopy. Subsamples were roughly divided and coated in gold for analysis using a scanning electron microscope. Transmitted light microscopy was used for cement identification with the thin section samples examined under cross polarised light to better identify the cements present. The University of KwaZulu Natal'sMicroscopy &Microanalysis Unit provided access to a high-resolution transmission electronmicroscope (SEM) used to further describe the cement fabric and relationship to cemented grains.

3. Results

The cemented beachrock outcrop was characterised by seawarddipping, planar laminated beds. It comprised moderately sorted medium to coarse sand, granules, occasional pebbles (pre-existing beachrock, granite and shale clasts), whole shells (disarticulated bivalves) and shell debris (1–12 mm in diameter). The framework grains (quartz- and feldspar dominated), constituting up to 50% of the sample, are sub-angular to sub-rounded with medium to low sphericity. The granules comprising feldspars and lithic fragments are more sub-angular, and account for a contribution of 25%. Pebbles (shale/beachrock/lithic fragments) account for ca. 10% of the observed clasts and display a sub-angular to rounded texture. Coarse grained laminations are interspersed throughout the exposed units and associated with increased heavy mineral content. The texture and composition of the outcrop are comparable to the surrounding unconsolidated beachface sediments.

The architecture of the deposit, described froma sediment encrusted storm water outfall, comprises an overall seaward prograding set of packages with distinct sub-packages (Fig. 3). Seaward-dipping prograding packages are overlain by vertically stacked shallowly landward-dipping units showing several phases of beachface building and aggradation of the backbeach (Fig. 3). The most seaward exposure shows steeply seaward-dipping planar beds (15° – 20°). The lower surface of each prograding package onlaps the upper surface of the previous package. Each package is 0.5–1 m in vertical thickness (thickening seaward) and 1–3 m wide (horizontal) in the seaward direction. The overlying landward dipping packages thin from the seaward edge (0.5 m) to landward where they pinch out.

Two cement fabrics (meniscus and acicular) are evident in thin section (Fig. 4a–e). Both occur in direct contactwith the framework grains, although the meniscus fabric is more common, accounting for 60–80% of the cement present, and always in direct contact with clasts. In contrast the acicular cement (accounting for 20–40% of the precipitated cement), while in direct contact with some clasts (Fig. 4d), postdates and overlies the meniscus cement (Fig. 4b,c). The acicular fabric radiates, at times randomly, into the pore space between grains forming acicular meshes. Individual needles arewell definedwith clear, straight, parallel crystal boundaries and chisel-like terminations (Fig. 4f). The meniscus fabric characteristically rounds the pore space between grains (Fig. 4a,b,e), thinning away from the grain-to-grain contacts (Fig. 4a).

The scanning electron micrograph shows the acicular and meniscus cement textures from the beachrock (Fig. 4f). Cement-free grain surfaces are evident either side of the cemented area between grains where needles, 20–30 μm in length and 2–3 μm wide, of cement grow into the pore spaces. Typically orientated perpendicular to the grain surface acicular meshes are common proximal to grain-to-grain contacts. Needles are chisel pointed, rather than blunt, and commonly form needle meshes that overly the meniscus cement which, when present, is always in contact with the framework clasts, and thinning away from the grain contacts.

4. Discussion

4.1. Maximum age of beachrock

The 2007 erosional period scoured down to bedrock, and no sand was present in the location where the beachrock was located in 2012. The 2011 erosional event,while not on parwith 2007, removed a significant volume of sediment fromthe beach, causing it to retreat landward past the point where the beachrock is now encountered. This means that both phases of beachrock cementation took place in the intervening 4–5 years between building of the new beach and uncovering of the outcrop on 3 February 2015.

4.2. Cementation

Cement fabrics typically vary in association with the zone in which they precipitate. However, although meniscus fabrics are typically characteristic of the vadose zone, both meniscus and acicular cement fabrics are associated with the marine-phreatic, marine-vadose, and meteoricphreatic zones (Flügel, 2004). The first-formed meniscus fabrics that dominate in the samples (Fig. 4), suggest initial cementation in marine and meteoric vadose zones of the upper intertidal to low supratidal zones (Adams andMacKenzie, 1998; Flügel, 2004). In contrast, acicular cements likely developed under saturated pore-space conditions, such as those occurring in the mid to lower intertidal mixing zone. The succession of cement types thus points to a change in diagenetic environment from dry (vadose) to wet (phreatic) conditions at the site of beachrock formation.

4.3. Cementation in relation to beach dynamics

The modern beach sedimentary architecture (Fig. 3) records several offlapping progradational and aggradational units that reflect several phases of beach reformation and growth since 2011. Subsequent erosion exposed the outcrop during the 2015 event.

Erosion and accretion of beaches is linked to a variety of factors including wave energy, sediment supply and antecedent beach state.

However, water table variations also play a role; beaches with a low water table tend to accrete while those with a high water table tend to erode (Grant, 1948). This linked behaviour of beach and water table appears to be reflected in the cementation of beachrock at the short timescales reported here: variations in saturation of the sediment pore-space and availability of carbonate in solutionwill have a direct influence on cementation processes and style. This is demonstrated by the relationship of two generations of cement observed in thin sections and micrograph. The meniscus cement likely representing the initial phase of sedimentation during undersaturated conditions. During increased saturation, associated with an increase in water table elevation relative to the deposit, acicular cements developed as a second stage of cementation.

This leads us to propose a model (Fig. 5) for rapid beachrock cementation that is related to linked changes in beach morphodynamics and water table position. Following erosion of the beach in 2011 (Fig. 5, t1), progradation of the beach face occurred due to seaward reworking of eroded sediment. The early-formed beach would have had a low water table that likely aided progradation through more easily mobilised sediments. Under these conditions the meteoric/marine mixing zone and interface between marine and meteoric influence shifts seaward, tracking the progradation of the beachface and seaward migration of the water table (Fig. 5, t2). The more landward portions of the prograded beach sediments are now stable (not being reworked on the beachface) and beyond the marine vadose influences on the backbeach/foredunes, however, they are still influenced by sea spray.

Initialmeniscus fabrics likely developed during cementation in this undersaturated meteoric vadose zone.

A subsequent relative rise inwater table associatedwith an erosional beach phase caused the marine/meteoric interface to shift landward as the beachface retrograded. At this stage (Fig. 5, t3), the proto-beachrock, partially cemented by the meniscus cements and still covered by the beachface now lay exclusively within the intertidal zone at the level of the marine vadose/marine phreatic mixing zone. This is evidenced by the stratigraphic architecture recorded by encrustations on the storm water outfall, proximal to the studied outcrop, which shows several phases of beach building and erosion (Fig. 3). The change in conditions from the undersaturated meteoric vadose zone to marine vadose/ marine phreatic mixing led to formation of acicular cement fabrics, either overlying the meniscus, or (in the absence of an early-formed meniscus cement) in direct contact with clasts (Fig. 4).

The duration of the buried phase is critical to the long-term preservation potential of the beachrock. If a complete erosion event such as that of 2007 and 2011 were to recur before the beachrock was well cemented, it would be destroyed. Indeed, the presence of reworked granules and pebbles of beachrock within the modern beach sediment is evidence of earlier phases of beachrock formation and destruction (Fig. 6). Such cycles may explain the relative scarcity of modern beachrock on the high-energy beaches of SE Africa.

There is meaningful debate regarding beachrock genesis in relation to sea level (as an indicator of sea level) with some in favour of supratidal genesis (Kelletat, 2006), yet others maintain that genesis is associated with the intertidal zone based on the cement character and stratigraphic architecture of the beachrock (Neumeier, 1998; Kneale and Viles, 2000; Vieira and Ros, 2007a, 2007b; Vousdoukas et al., 2005; Mauz et al., 2015). The latter argument is supported by the finding of this study with additional insight. The relationship between cementation and beach morphological flux during a particular sea level phase (regression; stillstand; transgression) is important in understanding the formation of cements during diagenesis. Thus,morphological change in the beach deposit may play a more significant role than anticipated in rapidly forming beachrock.

Cycles of beach progradation and retrogradation have previously been recognised (Strasser and Davaud, 1986), based on thin section analysis of 2000-year-old beachrocks of the Bahamas. They posit that the complete shallow subtidal to supratidal sequence, exposed on the carbonate-rich Bimini and Joulter Cays, reflects initial cementation in themeteoric phreatic and vadose zones, followed by secondary cementation in the marine vadose zone in response to a phase of coastal retrogradation.

Ourmodel supports that of Strasser and Davaud (1986) but in addition, we are able to demonstrate that initial and secondary cementation can occur in relatively short-term (bfive years) periods of cyclic beach progradation/retrogradation. Changes in style of Holocene beachrock cementation have been attributed to sea-level changes and linked changes in water table by many authors (e.g., Strasser et al., 1989; Cooper and Flores, 1991; Desruelles et al., 2009). Notwithstanding that interpretation, our results demonstrate that cementation changes that reflect changing vadose and phreatic zones can also be linked to short-term morphodynamic changes. This finding highlights the significance of understanding the setting in which beachrocks have formed. Further, short-term lateral changes in beach morphology during stable sea level as well as long-term, sea-level related processes may drive changes in cement precipitation; the difference between the two should be carefully considered. Last, this finding suggests that beachrock may be forming in numerous areas at present, however, it does so within the beach core rather than on the beach surface. Hence, its genesis is largely unaccounted for in the literature unless exposed through erosion.

Conclusions

We show unequivocally that variations in cementation related to variations In marine/meteoric zones, in accordance with beach progradation and retrogradation, is a valid model for beachrock formation. Rapid cementation is occurring at present, on a short timescale (four to five years), on Glenashley Beach and within a comparatively carbonate poor setting on an open, high-energy coastline. Changes in sea-level are not necessary to explain changes in cement texture or type. Horizontal migration of the mixing zone, and associated endmembers, can drive changes in cement texture and type at short timescales. Although beachrocks remain a useful and reliable tool in sea level reconstruction, careful consideration must be given to the morpho-dynamics of the setting in which beachrock formation occurs.

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Figures

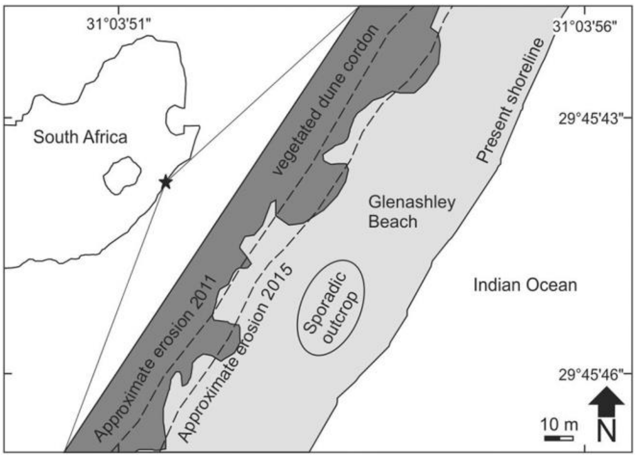

Fig. 1. Occurrence of contemporary beach rock at Glenashley Beach, Durban. Dashed lines indicate the landward limit of erosion from a 2011 storm event.

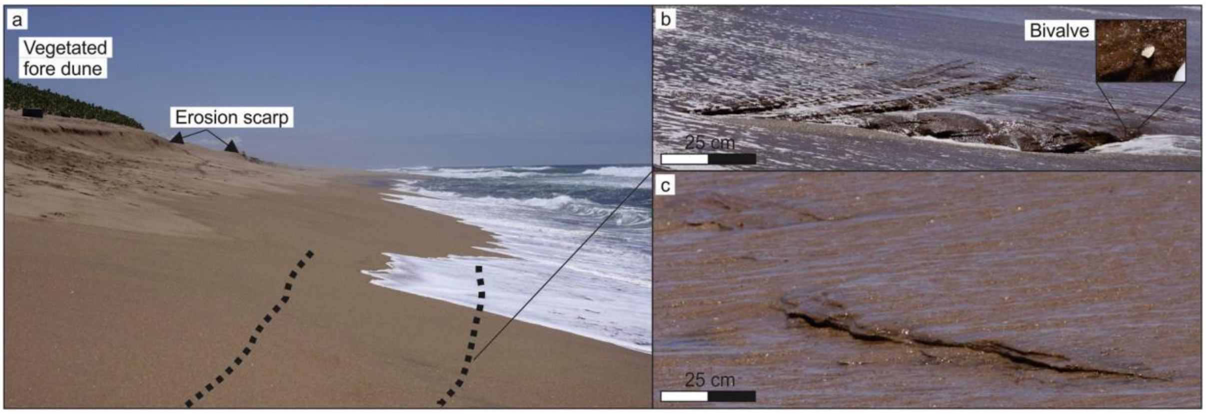

Fig. 2. (a) Beach face shortly after burial of the outcrop. Dashed lines show location of beachrock beneath the beachface. Note erosion scarp at the base of the foredune. (b) Outcrop of partially cemented beach rock, inset shows disarticulated bivalve shell. (c) Partially cemented beachrock being buried beneath unconsolidated beach sands.

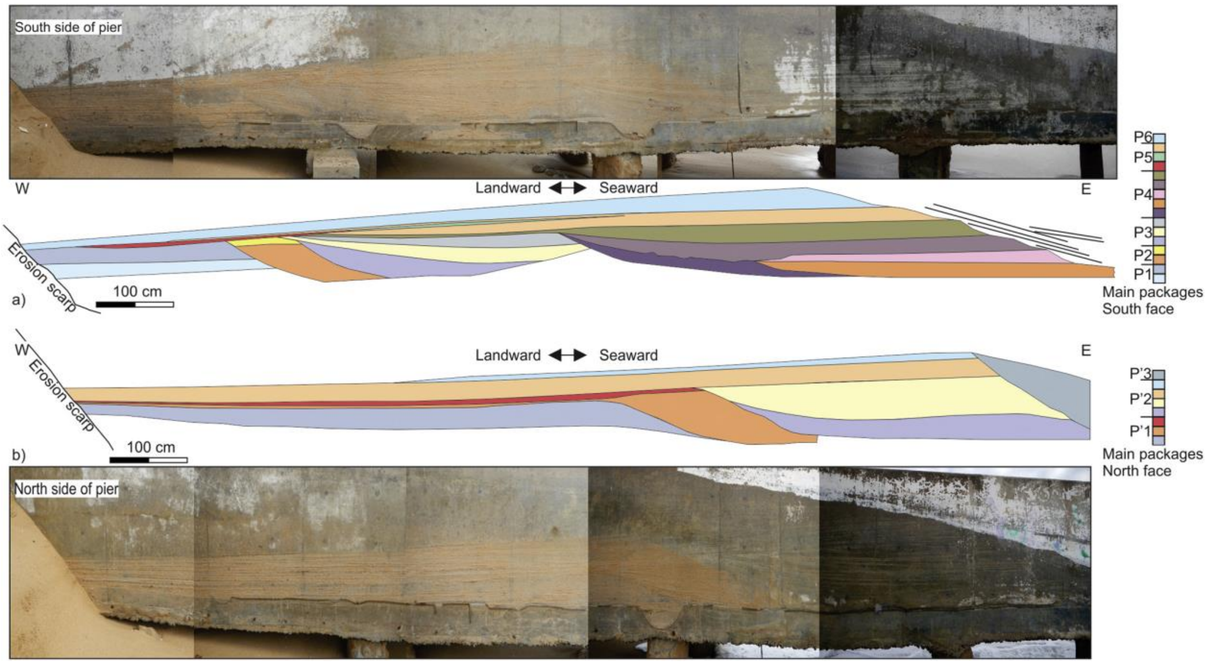

Fig. 3. The internal architecture of the contemporary beachrock based on encrusted outfall. (a)Multiple phases of beach progradation and backbeach aggradation (P1, 2, 3, 4), overlain by phases of aggradation (P5, 6). (b) Phases of beach building (P1, 2) capped on seaward extent by seaward dipping package, the base of which truncates the underlying packages (P3).

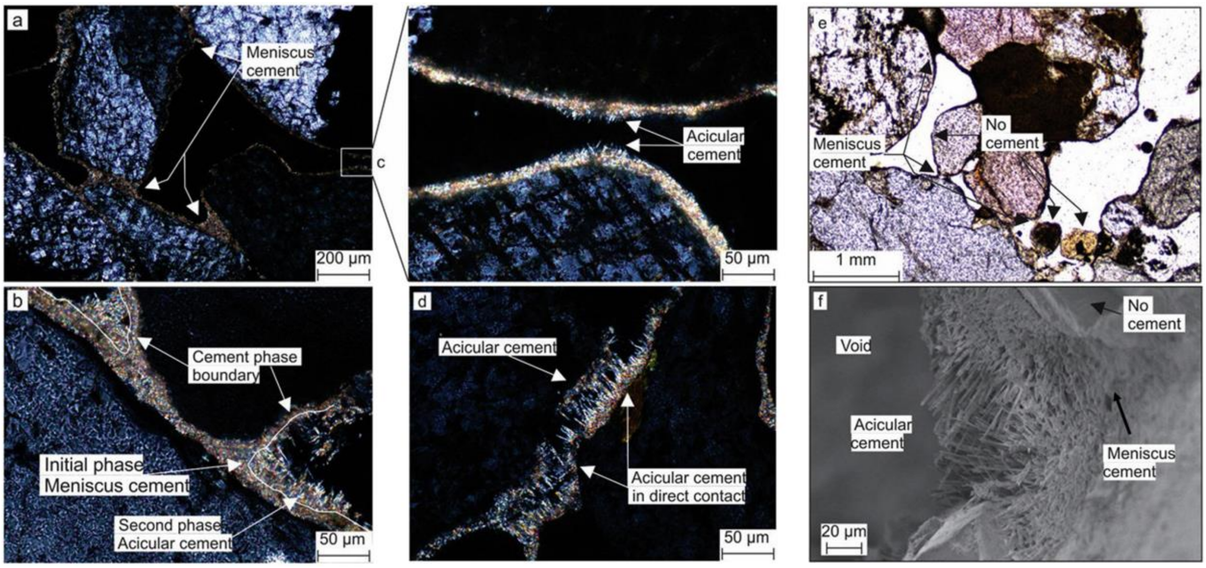

Fig. 4. (a) Meniscus cement texture at grain contacts (XPL). (b) Cementation relationship between initial meniscus cement and subsequent acicular cement (XPL). (c) Enlargement of (a) showing growth of acicular cement. (d) Acicular cement in direct grain contact, projecting into pore space. (e) Meniscus cement thins away from gran contacts, becoming absent.
(f). SEM image showing bare grain surfaces, meniscus and acicular cements.

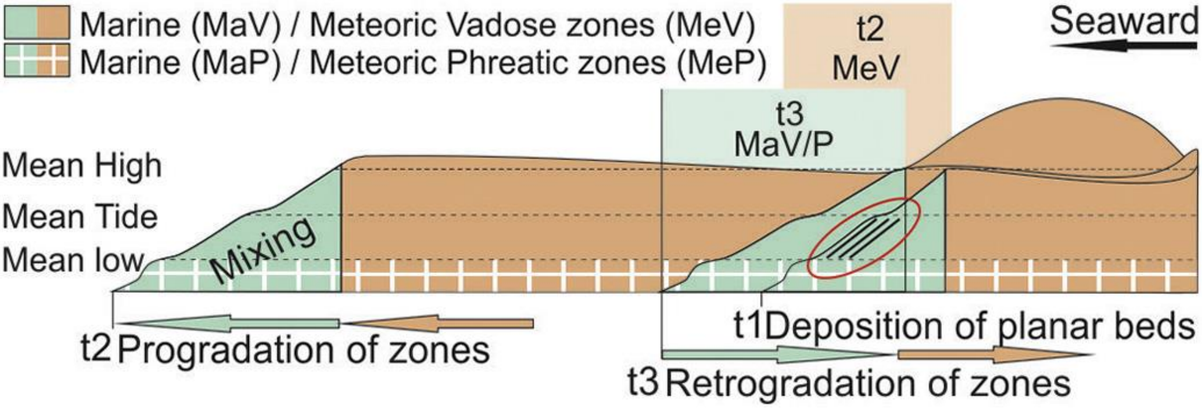

Fig. 5. Phases of initial deposition, t1; progradation and seaward shift of mixing zone, t2 (relative regression); retrogradation and landward shift of mixing zone, t3 (relative transgression).

Fig. 6. Reworked beachrock clasts are deposited up the beach profile belowthe backbeach, only exposed in the scarp upon erosion of the beach. Inset: close up view of beachrock pebbles and cobbles.