Beachrock development along the North coast of Cornwall

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Induration of beach material as a result of carbonate cementation to form sedimentary beachrock has rarely been reported from high latitude coastlines. The stratified beachrock exposed in the upper intertidal zone in Harlyn Beach, Harlyn Bay, north Cornwall, UK, appears homologous to the now poorly exposed cemented beachrock first described in the 1960's from the adjacent Little Cove in Mother Ivey's Bay, Cornwall. This study focuses on the field characteristics and mineralogy of the Harlyn beachrock deposit. The beachrock appears as an eroding relict deposit set in a currently high wave energy environment. Preliminary studies utilising petrography, scanning electron microscopy (SEM), Inductively Coupled Plasma Emission spectroscopy (ICP) and X-Ray diffraction (XRD) indicate that the Harlyn beachrock is composed of medium to coarse grained comminuted shell sand, lithologically comparable to the present beach sand, cemented by at least one phase of epitaxial low-Mg calcite. Limited development of beachrock with broadly similar features in the intertidal zone along the east side of the Camel Estuary, north Cornwall, UK, is also reported. Further work is required to develop a model for the development of beachrock in the context of geochemistry, sea-level fluctuations, local dune formation and movements and climate change during the Late Quaternary along the north Cornwall coast.

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Introduction

The occurrence of carbonate cemented beach sand along the north Cornwall coast, UK, (Figure 1), was described by Clarke (1968) who identified the intertidal cemented limesand reefs and cemented beach above high water in Little Cove, Mother Ivey's Bay, north Cornwall, as beachrock and by Bird (2000, p.115) who described the cemented sands in the adjacent Harlyn Bay, north Cornwall, as 'beach rock'. The beachrock deposits developed in Harlyn Bay have been well exposed over the past few years whereas the deposits in Little Cove are currently substantially covered by banked beach sands. However, laminae of beachrock are found adhering to the cliffs in Little Cove and the beach there is littered with beachrock pebbles, both of which appear identical to the Harlyn Bay material. Along the coasts of the British Isles, apart from the aforementioned, the few reported occurrences of beachrock include Tucker and Wright (1990, p.323), who refer to low-Mg calcite cemented beachrock on south-west UK beaches but give no localities or details, Pentecost (2005, p.305-6) who refers to widespread Quaternary beachrock in the UK but again with little in the way of detail, high-Mg calcite and aragonite cemented beach sand and beachrock on North Uist, Scotland (Kneale and Viles, 2000) and aragonite cemented beachrock in Clew Bay, Ireland (Sellwood, 1994).

The aim of this paper is to provide a preliminary description of the geomorphological and mineralogical characteristics of the beachrock occurring in the upper intertidal zone at Harlyn Bay on the north coast of Cornwall, UK, and to compare these with the beachrock described from other high latitude, high energy tidal beach localities along the NW European Atlantic coastline. The main area of beachrock investigated in this study is situated in Harlyn Beach (Figure 2). Beachrock-type deposits occurring inter-tidally in Daymer Bay and on the beach near Rock along the east side of the Camel Estuary, Cornwall, UK, (Figure 1) are briefly described. The present study was carried out over 2008-2009.

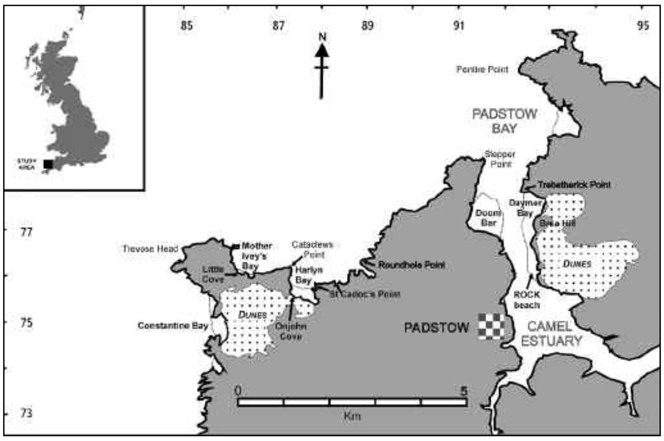

Figure 1. *Sketch map of north Cornwall coast between Constantine Bay and Pentire Point with location of Harlyn Bay, Daymer Bay, Rock Beach and landmark features. Inset map of the UK indicating the location, of the study area on the north coast of Cornwall.*

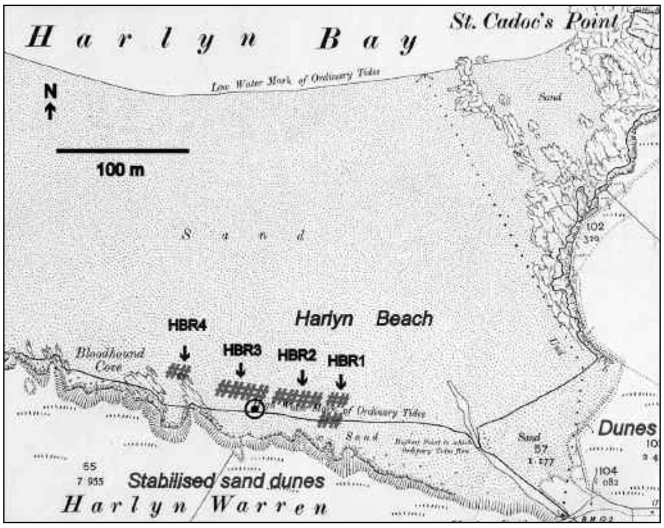

Figure 2. *Section of the 1907 Ordinance Survey map (Cornwall Sheet XVIII.14) showing the central and eastern parts of Harlyn Bay (Harlyn Beach), adapted to identify beachrock outcrops HBR1-3 at the back of Harlyn Beach and HBR4 adjacent to Bloodhound Cove (hatched areas) and adjacent dunes. Dotted circle indicates beachrock sampling location.*

Background

Beachrock is well-known from humid to arid tropical and sub-tropical coasts, for example, south Florida (Ginsburg, 1953), Canary Islands (Calvet *et al*., 2003), the Red Sea (Friedman, 2006) and north-eastern Brazil (Vieira *et al*., 2007). Beachrock is a term applied generically to partially to fully lithified, usually inter-tidal, non-compacted deposits that form *in situ* through the rapid mainly aragonite and/or high-Mg and/or low-Mg calcite cementation of indigenous beach sediment including sands and gravels of siliciclastic, bioclastic and volcaniclastic origin. Beachrock occurs on both marine and lacustrine coasts. Although the beachrock phenomenon has been recognized since the early 19th Century (Beaufort, 1817; Darwin, 1841) systematic petrographic and geochemical investigations effectively commenced in the mid-20th Century (Ginsburg, 1953; Stoddard and Cann, 1965). Beachrock formation in hot climates with micro-tidal regimes has been attributed to one of, or a mixture of, processes involving physico-chemical mechanisms including direct precipitation of $CaCO_3$ cement from meteoric water (Milliman, 1974), mixing of marine and meteoric water (Bernier *et al*., 1997), degassing of CO_2 in the phreatic zone by groundwater oscillations and in the vadose zone by tidal pumping (Hanor, 1978), biological action involving microbial degradation of organic matter, algal photosynthesis or encrustation/colonization (Krumbein, 1979) and bacterial calcification (Neumeier, 1998). Mechanisms for its formation in cold and temperate climates are currently more problematic. Here, where inter-tidal evaporation rates are comparatively low and sea water tends to be sub-saturated with respect to CO_2, much weight has been given to precipitation of $CaCO_3$ as beachrock cement from water of meteoric origin, in both phreatic and vadose zones.

Despite the fact that the mechanisms for beachrock formation are not fully understood (Turner, 2005; Gischler, 2007) its occurrence is of significant and sometimes controversial interest as a possible indicator of sea-level change (Kelletat, 2006; Knight, 2007; Kelletat, 2007) and palaeoclimate (Friedman, 2005; Mozeley and Burns, 2006; Friedman, 2006).

Although much of the literature on beachrock refers to its occurrence as a Holocene phenomenon, with estimated age of formation typically between 6 ka BP to 1 ka BP, reports of beachrock currently in formation are not infrequent and beachrock deposits are found in Pleistocene and earlier strata (Vousdoukas *et al*., 2007; Turner, 2005).

Because much of the earlier work focused on the development of tropical and sub-tropical beachrock its occurrence at higher latitudes has received less attention. It is, however, becoming increasingly apparent that beachrock formation is a widespread sedimentary process. Over the past few decades beachrock has been described from warm temperate to cold temperate European coastal locations ranging from low energy micro-tidal beaches in the Mediterranean (see Vousdoukas *et al*., 2007 (Table 1); Erginal *et al*., 2008; Ertek *et al*., 2008) to high energy meso-tidal and macro-tidal environments in the UK and Ireland, Portugal (Moura, 2007) and Spain (Rey *et al*., 2004).

Geographical and geological setting

Harlyn Bay, North Cornwall, UK

Harlyn Bay is situated on the north coast of Cornwall (latitude 50.5° N) some 5 km west of Padstow. The bay occupies the western part of a larger embayment between Cataclews Point to the west and Roundhole Point to the east. Harlyn Bay itself is approximately 0.75 km wide and is incised some 450 m into the Middle Devonian Trevose Slate Formation. The bay is bordered to the west by cliffs rising to 20 m at Cataclews Point, to the south by low dune-topped cliffs 3-8 m in height and to the east by a small headland, St Cadoc's Point, some 15 m in height. The bay is zeta-shaped (ζ) (Halligan, 1906), i.e. its radius of curvature decreases towards one end, in this case the east end. Harlyn Bay was probably formed in stages during Pleistocene marine transgressions by erosion of weakened cleaved slates adjacent to the fault/thrust system developed in the Trevose Head/Cataclews Point Marble Limestone Member and dolerite complex to the west and tidal incision of the mouth of a former river valley to the south east. A small stream occupies this valley currently and runs into the bay at its south-easterly extremity. The stream does not appear to have an appreciable sediment load and is not considered to contribute significantly to natural beach nourishment. Active dunes fringe the area to the south west and east of the stream whilst dunes to the south west of Harlyn Bay (Figure 2) have been stabilised by the development of properties in the village. To the west of the bay extensive dunes, probably of late Holocene age, have developed and these contain significant evidence of Mesolithic to Iron Age occupation (Whimster, 1977). These are currently stable and cover the isthmus to Constantine Bay 2 km to the west (Figure 1). Run-off water from the dunes fringing Harlyn Bay has led to considerable cliff-side colonisation by algae and bryophytes and, in Onjohn Cove, at the west end of Harlyn Bay, $CaCO_3$ enriched meteoric water is considered to have been instrumental in the formation of active and relict tufa cascades, as reported elsewhere in Cornwall (Howie and Ealey, 2009). Both the dune sands adjacent to Harlyn Bay and the beach sands in the bay are composed predominantly of comminuted shell fragments. The origin of the dune sand is unclear; Crawford (1921) considered that it accumulated as a result of prevailing westerlies blowing onshore from the beach at Constantine Bay.

The sand on Harlyn Beach is predominantly composed of comminuted shell which reflects the abundance of the molluscan fauna in Harlyn Bay (Warwick and Turk, 2002). Mid to upper beach shell pavements composed of fresh, broken and rolled low intertidal to sub-littoral zone molluscan material (including *Muricidae, Mytilidae, Nassariidae, Pectinidae* and *Turridae*) are frequently observed, particularly in the eastern part of the bay. Harlyn Bay is considered to be "a 'sand catchment' beach fully exposed to the open sea" (Warwick and Turk, 2002). Current evidence indicates that the sand accumulation on Harlyn Beach (Figure 2) in Harlyn Bay (Halcrow, 1999) occurs as a result of littoral drift and forms a sediment sub-cell mainly consisting of the comminuted calcareous skeletal remains of the offshore species pool.

Extensive calcareous sand and mud shoals extend at least from Pentire Point westwards, into the Camel Estuary and beyond Trevose Head (Figure 1) (Reid *et al.*, 1910). These sands, with calcium carbonate content in Harlyn Bay of 94%, in Padstow Harbour of 86% and Trevose (Mother Ivey's Bay) of 92% (Karkeek, 1846, p.44), are amongst the most calcareous in the UK. Accumulations of this material are so great around this part of the coast that it was extensively dredged and collected from beaches as 'lime sand' for use as agricultural lime dressing, from at least the time of James I, until comparatively recently to the point where legislation was emplaced to control its removal (Hansard, 1947).

Harlyn Bay experiences a macro-tidal regime with extreme annual tidal range of 6 m (1.5 m during neap tides and 7.5 m during spring tides (data from Newquay tide tables)). Wave heights in the bay average 1-2 m, with occasional storm waves of up to 5 m. Morphodynamically the beach is classified as intermediate (Masselink and Hughes, 2003; Scott *et al.*, 2007) with cusps and horns developed in the mid to upper intertidal zone. Sea temperatures along the SW peninsula range annually between 9° and 15°C (Hayward and Ryland, 2006). The area experiences a maritime climate with mean minimum temperature of 3.5°C and mean maximum temperature of 19.1°C and annual rainfall averaging 1043 mm (Meteorological Office data, St Mawgans 1971-2001). The prevailing currents along this part of the coast are predominantly south westerly and winds west to north westerly. However, the constraints of the northerly jutting headlands to the west and east of the embayment cause current deceleration and assist in the accumulation of drift sand in the north east facing Harlyn Bay. The Cataclews Point and St Cadoc's Point headlands protect the beach from erosion by westerly and easterly storms respectively although rare northerly storms tend to partially scour the beach, as happens during the autumn and winter in several of the bays along the north coast of Cornwall.

Harlyn beachrock - location and description

The Harlyn beachrock crops out at mean high water level (Figure 2) and just below in Harlyn Beach (GPS-NGR SW 87685 75422: WAAS accuracy ±3-5 m) and extend westwards to Bloodhound Cove (GPS-NGR SW 87559 75477: WAAS accuracy ± 3-5 m).

The beachrock outcrops total some 150 m in length along the beach, are up to 10 m wide and 1.5 m thick. The outcrop is not continuously exposed along its full length as beach sand is variably deposited in the interspaces where the beachrock deposits are either eroded away or dip below beach level. Four beachrock areas were surveyed, three closely associated, HBR1, HBR2, HBR3 (Figures 2 and 3) and HBR4, which is located approximately 50 m to the west at the entrance to Bloodhound Cove (Figure 2).

The east section HBR1 has an exposed surface area of approximately 50 m^2 and at its easterly outcrop is cemented to the wave cut Middle Devonian Trevose Slate Formation platform (Figures 3 and 4). The seaward part of the section dips approximately 04°-07° N with strike 280°, which is parallel to the drift line of the modern beach; the total thickness of HBR1exposed above beach level is 1.5 m. The upper part of HBR1 is weathered grey to a depth of a few millimetres on the exposed surfaces and composed of a highly eroded but tough, coarse to very coarse grained cemented sand. The stepped erosion configuration (Figure 4) indicates that this section is a remnant of once much thicker beachrock sheets.

Two larger beachrock areas to the west, HBR2 and HBR3, which occupy an area of approximately 200 m^2 and 400 m^2 respectively, show distinctive backshore vertical incision and horizontal erosion. These beachrock sheets have a seaward dip of 04°-07° N and a strike of 280° which is approximately parallel to that of the modern beach (Figure 3). The thickness of these sections above beach level is up to 0.8 m and below beach level extend down at least a further 0.3 m. Whether or not these sections rest on the slate platform has not been ascertained. The upper surface of these sections shows wave-induced fluting, runnels and cavitation and extensive algal colonization (Figure 5). Differential erosion of the vertical backshore exposed face of the sections reveals planar cross bedding with individual units of 10 to 30 cm thickness composed of laminae and thin beds, averaging 0.5-1 cm in thickness, of coarse to very coarse grained cemented sand. Weathering between exposed laminae occurs laterally to a depth of a few millimetres and between beds to a depth of several cm. Horizontally oriented well rounded slate pebbles, cobbles and small boulders, ranging from less than 1 cm to over 30 cm in diameter, infrequently occur (Figure 6).

Figure 3. *Harlyn Beach looking east showing the location in the upper intertidal zone of beachrock outcrops HBR1, HBR2 and HBR3, and their relationship to the wave cut Middle Devonian Trevose Slate Formation (Tr Sl platform). The algal coated beachrock sheets show a seaward dip of 04-07° N, easterly strike approximately parallel to that of present beach and vertically eroded backshore profile. Contact between the beachrock and slate platform is arrowed. The approximate length of the three beachrock exposures is 100 m.*

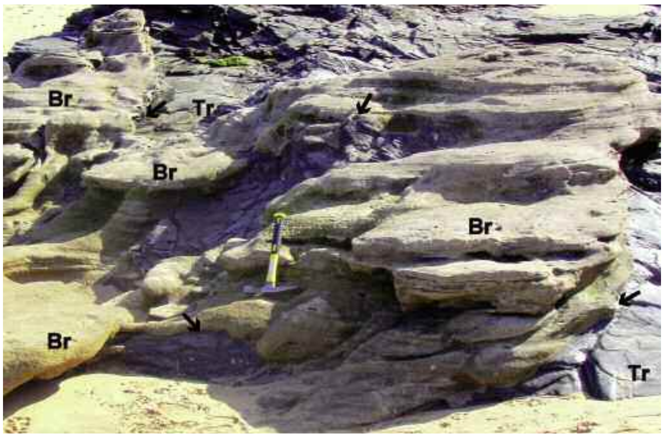

Figure 4. *1.5 m high beachrock (Br) outlier at HBR1, cemented to the Middle Devonian Trevose Slate Formation wave cut platform (Tr), showing stepped erosion configuration of beachrock sheets. Contacts between slate and beachrock are arrowed.*

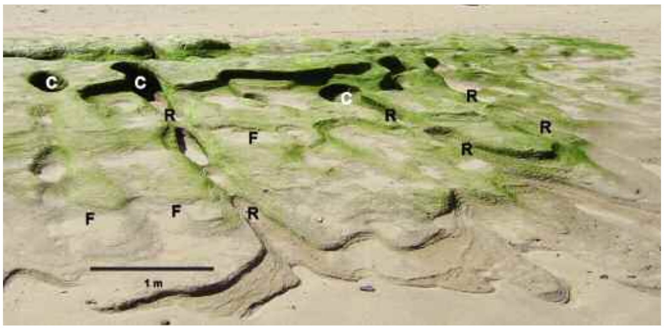

Figure 5. *Upper exposed seaward dipping face of beachrock at HBR3 exhibiting extensive surface algal growth and erosion pattern of wave-induced fluting (F), runnels (R) and cavitation (C).*

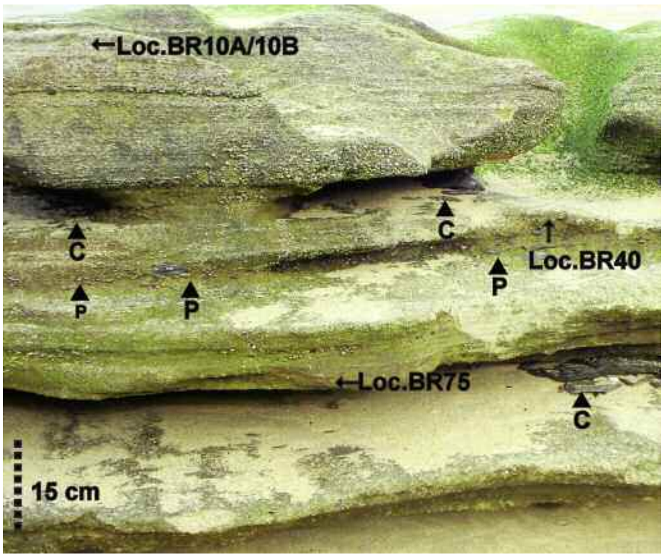

Figure 6. *Vertically eroded backshore facing elevation of beachrock at HBR3 (location GPS-NGR SW 87560 75485) showing differential erosion of beds and laminae and occasional horizontally oriented beds of slate pebbles (P), cobbles and boulders (C). Locations of sampling points shown: Loc. BR10A, Loc. BR10B, Loc. BR40 and Loc. BR75.*

Figure 7. *Beachrock sheets at HBR4, Bloodhound Cove. Excavated section shows fresh, non-eroded outer surface and horizontal and vertical jointing of beachrock sheets (arrowed).*

Figure 8. *Seaward dipping laminae of remnant beachrock (arrowed) cemented to cliff face in Bloodhound Cove indicating possible vertical extent of former beachrock sheet (dotted line).*

HBR4 was exposed in 2008 (but covered by sand early in 2009) at the entrance to Bloodhound Cove. This section occupies an area of approximately 100 m^2. Excavation of this section below the beach revealed both vertical and horizontal jointing (Figure 7); the section is at least 80 cm thick, has a fresh, non-eroded appearance where excavated, is medium grained and slightly softer than the beachrock in upper exposed parts of the section and extends into the beach. Slabs of detached beachrock up to 1 m x 2 m and 20-30 cm thick litter the area in and around the cove. Remnant laminae of coarse grained beachrock, dipping ~05° seawards, are seen adhering to the slate cliff face, on the west side of Bloodhound Cove, up to ~75 cm above the surface of the present exposed HBR4 outcrop (Figure 8).

Camel Estuary

Daymer Bay and Rock Beach are situated on the east side of the Camel Estuary approximately 3 km and 1 km north of Padstow respectively (Figure 1). Daymer Bay is flanked to the north by Trebetherick Point, to the east by stabilised dunes and continues south around Brae Hill to connect to Rock Beach. A stream runs into Daymer Bay from the east through the dunes. Run-off water from the dunes is in evidence as small streams crossing Rock beach, where a backshore foredune has developed. Both the bay and the beach are sheltered from the full force of tidal flow by their situation facing Stepper Point, the promontory to the west, and the extensive sand shoal of Doom Bar in the mouth of the Camel Estuary. The beaches in the Camel Estuary were extensively dredged for lime sand (Merefield, 1989) for several hundred years; Karkeek (1845) reported 86.5% calcium carbonate in the sands at Padstow.

Daymer Bay and Rock Beach cemented sand - location and description

A cemented beach sand deposit was temporarily uncovered early in 2009 in the north central part of Daymer Bay. This outcrop extends in a rough elliptical arc some 175 m N-S by 400 m E-W (GPS-NGR SW 927 775) with thickness varying between 20 and 30 cm above the beach and, in places extends some 30-40 cm below beach level. The surface of the cemented deposit exhibits variable dip and strike and is considerably disturbed, with the beds near the edge of the exposure vertically disposed and those close to the centre of the exposure deeply undercut (Figure 9). The upper part of the deposit contains a thin, intermittent conglomeratic bed

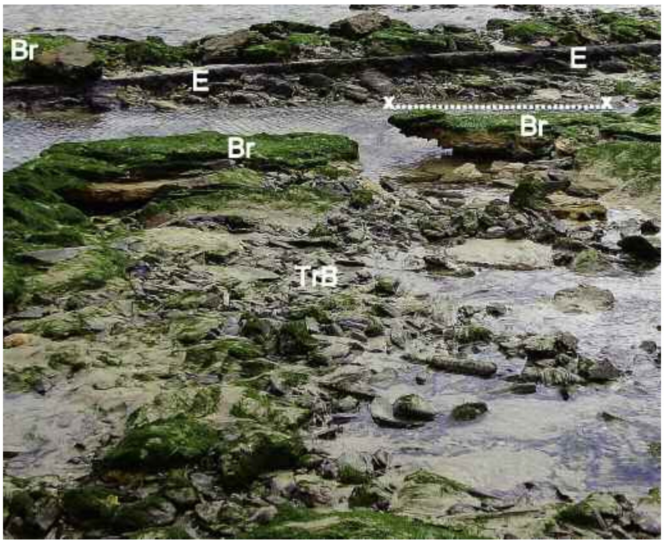

Figure 9. *Beachrock sheets in Daymer Bay, (Br) overlying (?) Tregunna Boulder Bed (TrB) and earthy 'submarine forest bed' (E). For scale, the undercut in situ beachrock slab in the centre (arrowed) is ~1 m in width.*

consisting of local slate and quartzite pebbles and cobbles together with shells and fragments of marine molluscs, especially *Mytilus edulis*. In the central part of the exposure the deposit appears to lie directly on a compacted bed of purple and green worn slate pebbles, cobbles and quartz vein fragments, possibly the Trebetherick Boulder Bed (Scourse, 1997). Around the perimeter of the exposure the cemented sand overlies a grey and friable earthy sand bed some 30-40 cm in thickness, which is rich in terrestrial and fresh water mollusca and plant remains, including partially carbonised branches, twigs, seeds, trunks and remains of rooted tree stumps. This earthy sand bed is interpreted as the Daymer Bay 'submarine forest bed' described by Henwood (1858). The cemented sand deposit in Rock beach occurs 100 m NW of the ferry jetty (GPS-NGR SW 927 758) and extends intermittently in the upper tidal zone ~15 m along the beach, is up to 3 m wide with maximum thickness of ~10 cm. The deposit lies directly on beach sand.

Sampling and methods

For this study hand specimens of beachrock from the backshore vertical exposures of HBR1, HBR2, HBR3 and HBR4 in Harlyn Bay were collected and examined visually in the field and laboratory. The main criteria for selection of samples for further analysis were textural homogeneity and depth of weathering. Outcrop HBR1 appeared to be of a higher horizon than the other outcrops and showed significant alteration and erosion. Samples from outcrop HBR4 were generally soft and fairly friable. The beachrock deposit constituting the linked outcrops HBR2 and HBR3 showed clear horizontal textural homogeneity with little surface alteration and was well cemented along the whole length of exposure. A point approximately midway along the linked outcrops was therefore considered to be representative of the deposit and a total of four samples of beachrock were taken from HBR3 at location GPS-NGR SW 87560 75485: WAAS accuracy ±3-5 m (Figure 6).

Two samples (Loc. BR10A and Loc. BR10B) were collected ~10 mm below the weathered surface zone of HBR3. Samples of Loc. BR10A and Loc. BR10B were resin embedded and each cut in a plane orientated perpendicular to and normal to the beachrock bedding plane. The sample Loc. BR10A was prepared as a thin section for examination by transmitted light microscopy. A sample of Loc. BR10B was prepared for analysis by Inductively Coupled Plasma Emission spectroscopy using a Varian Vista PRO spectrometer (ICP). Another sample of Loc. BR10B was prepared as a polished surface for reflected light imaging using a Ziess Axioplan microscope fitted with a JVC KY-F70 CCD camera in conjunction with Automontage imaging software. Normally, reflected light is used to image materials that are opaque to light, because these produce a focussed image from a single plane (i.e. the polished surface). However, there are certain advantages when transparent materials are viewed in reflected light; fine inclusions and textural intergrowths with subtly different anisotropic properties can be more clearly imaged without significant loss of intensity by using partially-crossed polars. For transparent materials viewed using a reflected light microscope, the light penetrates into the material and an image can be formed from a chosen single depth in focus (i.e. for a plane of focus just below or at the surface). Using Automontage software a sequence of through focus planes can be added together to produce a single sharp-focussed image with an apparent depth of focus greater than that of a single image. In this way a 'transmitted light' image can be produced from a slice thinner (less than ~5 microns) than could be physically manufactured by cutting and polishing (Cressey *et al.*, 2008). When a thin section (normally ~30 microns in thickness) is viewed in transmitted light, there will always be a blurred contribution from the whole thickness in any image recorded.

Two samples, collected on the basis of differing grain size, one from 40 cm below (Loc. BR40) and the other from 75 cm below (Loc. BR75) the vertical backshore face of HBR3, were fractured and stub-mounted, uncoated, for examination using scanning electron microscopy (Jeol JSM 5400LV SEM).

A sample of beachrock from HBR4 and a sample of nearby beach sand were each washed, dried and weighed and subsequently digested in cold 3M hydrochloric acid for 24 hours to remove calcareous material. The acid insoluble residues were dried and weighed. The gravimetric difference of samples before and after acid digestion established the total calcium carbonate content. The residues were ground for X-Ray diffraction (XRD) analysis, which was performed with a NONIUS Diffractometer with an INEL curved position-sensitive detector. XRD data were analysed using STOE search-match software.

Samples of cemented sand were collected from the Daymer Bay outcrop (DBR1) and the Rock Beach outcrop (RBR1) for determination of total calcium carbonate as described above for the sample from HBR4. Optical microscopy was used to determine the mineralogy of the acid insoluble residues. A sample from Daymer Bay (DBR1) was fractured and stub mounted, uncoated, for scanning electron microscopy.

Harlyn beachrock - composition and texture

In terms of overall composition the Harlyn beachrock sand component is comparable to modern Harlyn beach sand in terms of grain size, grain shape, $CaCO_3$ content and residual mineral content (see Table 1). The samples of beach sand and beachrock from location HBR4 contain approximately 88% and 90% $CaCO_3$ respectively after 3M HCl digestion. XRD showed that the acid-insoluble residue from the beachrock sample contained quartz, albite-rich plagioclase (with about 15% of the Na replaced by Ca), muscovite and Fe-bearing clinochlore (chlorite). The beach sand acid-insoluble residue XRD showed

Location	Grain size (phi)	$CaCO_3$ content$^+$	Residual minerals
Harlyn Bay Beachrock – HBR4	1.5 to -1	90%	*Quartz, muscovite, albite-rich plagioclase, Fe-bearing clinochlore (chlorite)
Harlyn Bay contemporary beach sand	1 to -0.5	88%	*Quartz, muscovite, plagioclase, kaolinite
Daymer Bay Beachrock - DBR1	2 to 1.5	78%	**Quartz, mica, feldspar, carbonised (plant) fragments
Rock Beach Beachrock - RBR1	2 to -1	84%	**Quartz, mica, feldspar, carbonised (plant) fragments

Table 1. *Summary of grain size, $CaCO_3$ content (+ determined gravimetrically by difference after digestion of samples in 3M HCl) and qualitative analysis of residual minerals (* determined by X-Ray diffraction, ** by optical microscopy) in samples of Harlyn beachrock (HBR4), Harlyn Bay contemporary beach sand, Daymer Bay beachrock (DBR1) and Rock Beach cemented sand (RBR1).*

quartz, plagioclase, muscovite and kaolinite but no chlorite. The diffraction peaks of the feldspar in the beach sand residue indicate that it contains a little more Ca than the plagioclase in the beachrock residue. Sampled beach sand grain size was 1 to -0.5 phi (500 µm to 1.5 mm).

In the areas sampled (HBR1–HBR4) the texture of the beachrock sand component varies vertically but not horizontally in terms of grain size and grain shape. Where exposed by erosion the beachrock sheets are planar with laminae and thin beds of moderately sorted to very well sorted, medium to very coarse grained, sub-rounded to well-rounded cemented comminuted shell, particle size 1.5 to – 1 phi (375 µm to 2 mm). Texturally, the laminae and thin beds extend considerable distances horizontally with little variation in grain size. The laminae develop into beds 10 to 30 cm thick, but little evidence of this is seen in non-eroded samples. Hand specimens are hard to very hard, are non-fissile with a blocky fracture.

Rounded to well-rounded slate pebbles to small boulders, varying in size between a few mm to ~30 cm in diameter, infrequently occur in the beachrock, usually in discrete, conglomeratic beds (Figure 6). Occasional angular rock fragments are seen. The clast distribution is comparable with that found in the modern beach. No whole shells were observed in the Harlyn beachrock during the present study and few shell fragments were identifiable in hand specimens, although shell fragment pattern and colour indicate the presence of *Pectinidae* and *Mytilidae.*

Daymer and Rock cemented sand - composition and texture

Samples of the Daymer cemented sand showed variable induration from very friable at ~30-40 cm below the beach to friable, with fissile fracture, at the top of the exposure. A sample from the top of the deposit (Loc. DBR1) contained approximately 78% $CaCO_3$ after 3M HCl digestion. The acid-insoluble residue, examined optically, contained sub-rounded quartz, mica, feldspar, slate grains and carbonised plant fragments (Table 1). The cemented sand is composed of well sorted to very well sorted fragments of comminuted shell and rounded to well-rounded mineral grains between 2 to 1.5 phi (250 µm to 750 µm).

The Rock Beach material was a hard cemented sand with a blocky, non-fissile, fracture composed of well sorted fragments of comminuted shell and mineral grains between 2 to -1 phi (250 µm to 750 µm). A sample from the top of the deposit (RBR1) contained approximately 84% $CaCO_3$ after 3M HCl digestion. The acid-insoluble residue, examined optically, contained sub-rounded quartz, mica, feldspar, slate grains and carbonised plant fragments (Table 1).

Petrographic and mineralogical characteristics

Petrographic examination and scanning electron microscopy (SEM) of the four samples from Harlyn beachrock section HBR3 (Loc. BR10A, Loc. BR10B, Loc. BR40 and Loc. Br75) at low magnification reveals beachrock with a porous fabric (Figure 10a: Loc. BR75; SEM) composed of moderately to well sorted, partially spar cemented, mainly equigranular, fragments (mostly of comminuted bivalve shell with occasional gastropods, infilled with calcite spar, and echinoid spines), sub-rounded to rounded grains of quartz and mica (Figure 11a: Loc. BR10A; thin section), and occasional slate granules, 2 to >4 mm long (Figure 11d: Loc. BR10A; thin section). The preferred orientation of shell grains appears parallel or sub-parallel to the fracture plane (SEM) and bedding (orientated sections). A moderate degree of porosity is clearly seen as voids between grains (Figure 10a; Loc. BR75; SEM and Figure 11a; Loc. BR10a).

At higher magnification shell grain dissolution and internal alteration are variable, with some bivalve fragments retaining prismatic/nacreous structure (Figure 11b: Loc. 10B; polished section; Automontage) and others showing surface dissolution and micro-boring (Figure 10b: Loc. BR75 SEM; and Figure 11c: Loc. 10B; polished section; Automontage) possibly by algae or bacteria. Intergranular voids are partially filled (Figure 10b: Loc. BR75; SEM), lined or filled (Figure 11b) by a generation of bladed or equant calcite crystals approximately 25-50 µm long. These appear to have grown from grain surfaces with and without micritic nucleation, creating interlocking polygonal boundaries where grains are close together but not in contact (Figure 11b). Micro-boring and surface dissolution appear restricted to fabric shell grains; there is no evidence of dissolution or micro-boring in the calcite cement phase.

Framework shell and other small grains adjacent to granules show evidence of interrupted flow, under gravity, over the larger granules. These grains appear to be cemented by spar development in descending position suggesting rapid calcite precipitation (Figure 11d). Indications of a second phase of precipitation, or infiltration of 'lime mud' (*sensu* Clarke, 1968) into voids, is seen where earlier calcite spar cement and framework grains are coated with a layer containing small (<5 µm to 20 µm) angular lithic, calcitic and bioclast fragments set in an amorphous cement (Figure 10c: Loc. 10B; polished section; Automontage). SEM examination of the beachrock sample Loc. BR40 indicated a moderately sorted fabric composed extensively of subhedral to euhedral equant and bladed calcite both cementing and enveloping grains. No evidence of compaction of framework grains or pore space was seen in the beachrock samples examined in this study.

XRD analysis of the Harlyn beachrock sample Loc. BR10B suggested that a cation (or cations) smaller than Ca is (are) substituted in the calcite structure. ICP analysis on the sample established that the carbonate has 95.9% Ca, with 2.3% Mg and 1.8% Fe^{2+} in the 'Ca' site of the carbonate phase, indicating an impure low-Mg calcite with stoichiometric formula ($Ca_{0.959}$ $Mg_{0.023}$ $Fe_{0.018}$) CO_3.

One sample from Daymer Bay (Loc. DBR1) was examined using SEM. A framework fabric of equigranular shell fragments and sub rounded to rounded grains cemented by bladed calcite (Figure 10d, SEM) is seen, similar in morphology to Harlyn beachrock from Loc. BR75 (Figure 10b).

Discussion and summary

Harlyn Bay and Little Cove are alike in geomorphological setting with both locations cliff-backed although the cliffs behind Little Cove are not currently dune-topped. Clarke (1968) therefore concluded that some of the calcite cement in the Little Cove beachrock probably originated from water percolating through thin limestones in the cliffs around the cove rather than from dune sands although he considered that this was not a sufficient explanation for the extensive beachrock development in the cove. Clarke (1968) reported that the extent of the beachrock in Little Cove was some 35 m long, 18 m wide and up to 4.5 m thick (including an undercliff bank above HWMST). Although the beachrock in Harlyn Bay is now nowhere near as extensive as that in Little Cove there are indications that it was formerly a much thicker deposit. The stepped sequence at HBR1, the remnant laminae in Bloodhound Cove and the measured depth in the beach, taken together, suggest that the original thickness may have exceeded 2 m along a considerable length of the undercliff behind Harlyn Beach. Sedimentary features, including grain size, grain sorting and pebble and cobble distribution, which resemble the current beach profile, are well preserved in the Harlyn beachrock. In addition, the overall $CaCO_3$ composition, i.e. comminuted shell content and residual mineralogy is comparable to that found in the sand from the present beach. The present beach is however subject to considerable tidal scouring and the environment is probably not currently conducive to beachrock formation.

Clarke (1968) reported considerable vertical variation in lithology, texture and petrology in the Little Cove beachrock with aragonite (presumably comminuted shell material) and calcite grains (ranging from recognisable shell grains to pellets) variably cemented, mainly at grain contacts by crystalline calcite, but sometimes by calcite partially filling pore spaces. He interpreted the crystalline grain contact calcite cement as the primary cement and the pore filling calcite as secondary cementation resulting from solution of the outer surface of grains. As he found that calcite grains increased upwards and aragonite grains increased downwards he inferred that the highest part of the bank was the oldest on the basis that aragonite was likely to be more stable in the presence of seawater.

Optical microscopy and SEM examination of a small but representative number of Harlyn beachrock samples during the present study revealed little micrite, no significant acicular calcite and little or no evidence of meniscus cement which would be indicative of a vadose environment. First stage pore filling and intergranular cement in all the samples examined consisted of equant to bladed low-Mg calcite crystal growth indicative of generation in a freshwater phreatic environment (Sellwood, 1994). Micro-boring of shell fragments by algal or bacterial action predated the formation of calcite cement and is not considered to have contributed to cement formation. Little or no compaction of framework grains during initial deposition or later is evident from the porous texture of the beachrock. There is some petrological evidence that gravity induced grain flow around larger clasts was interrupted and set by cementation, suggesting that early calcite-rich fluid invasion and subsequent crystallisation had been rapid. A further stage in beachrock diagenesis is suggested by the invasion of the cemented fabric by infiltrating fluids depositing ‘lime mud’ around the periphery of pore spaces, lining both the earlier precipitated equant calcite spar cement and original uncoated grains.

The chemical analysis (ICP) of beachrock carbonate (sample Loc. BR10B) indicates a non-stoichiometric mineral with the formula $(Ca_{0.959}\ Mg_{0.023}\ Fe_{0.018})\ CO_3$. This composition is consistent with the shift in the main X-Ray diffraction peak for the calcite in the beachrock to a smaller spacing than for pure $CaCO_3$ and confirms that this peak shift results from the presence of Mg^{2+} and Fe^{2+} cations, which are smaller than Ca^{2+}, substituting in the calcite structure. Since the main fabric of the beachrock is comminuted shell (aragonite and calcite) this finding constrains the Mg-Fe-calcite to a beachrock cement phase.

Bird (2000) suggested that the Harlyn Bay ‘beach rock calcite cement had been supplied by seepage of carbonate water from the hinterland’. Tucker and Wright (1990) alluded to beachrock in south-west UK ‘cemented by low-Mg calcite from meteoric waters at the back of the beach’. Merefield (1989) described the carbonate mineralogy and geochemistry of dune sands from St Minver on the east side of the Camel Estuary behind Daymer Bay. He drew attention to the prevalence of aragonite and low-Mg calcite associated with the comminuted molluscan component of the dune sands, shoreline and estuarine sands in SW England. It is likely that

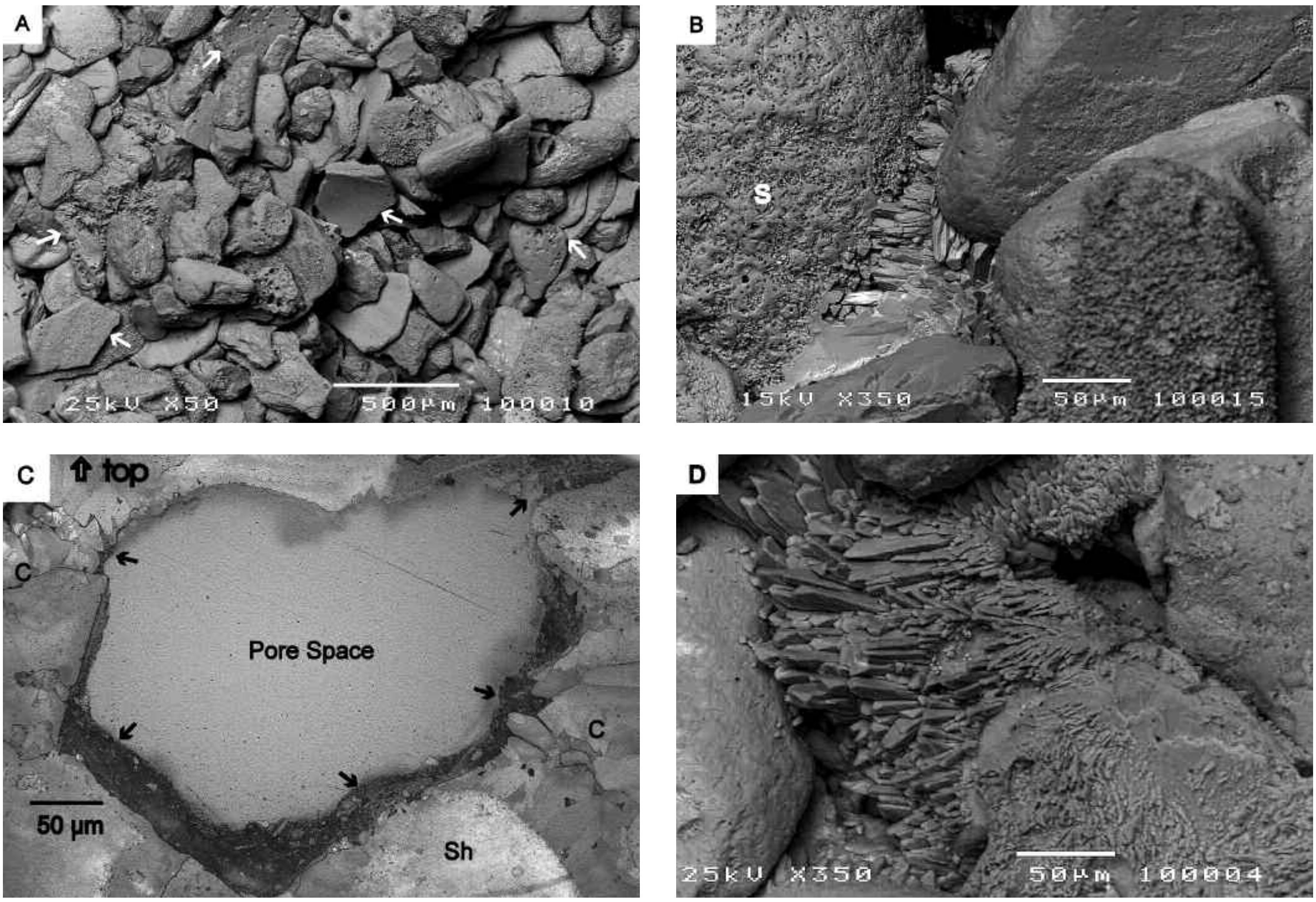

Figure 10. ***(a)*** *Loc. BR75: SEM; beachrock with porous fabric composed of moderately to well sorted, mainly equigranular, fragments of bivalve shell (arrowed), some showing dissolution, and sub-rounded mineral grains.* ***(b)*** *Loc. BR75: SEM; showing surface dissolution and possible micro-boring of shell grain (S) and bladed equant calcite crystals up to 50 µm long partially infilling and cementing grains (centre).* ***(c)*** *Loc. BR10B: polished section: partially crossed polarisers; Automontage; showing indications of a second phase of precipitation (arrowed) partially infilling pore space and coating earlier calcite equant spar cement (C) and shell grain (Sh); second phase containing small (<5 µm to 20 µm) angular lithic, calcitic and bioclast fragments set in an amorphous cement.* ***(d)*** *Loc. DBR1: SEM; beachrock grains infilled and cemented by bladed calcite; cf. Harlyn beachrock Loc. HBR75 (Figure 10b).*

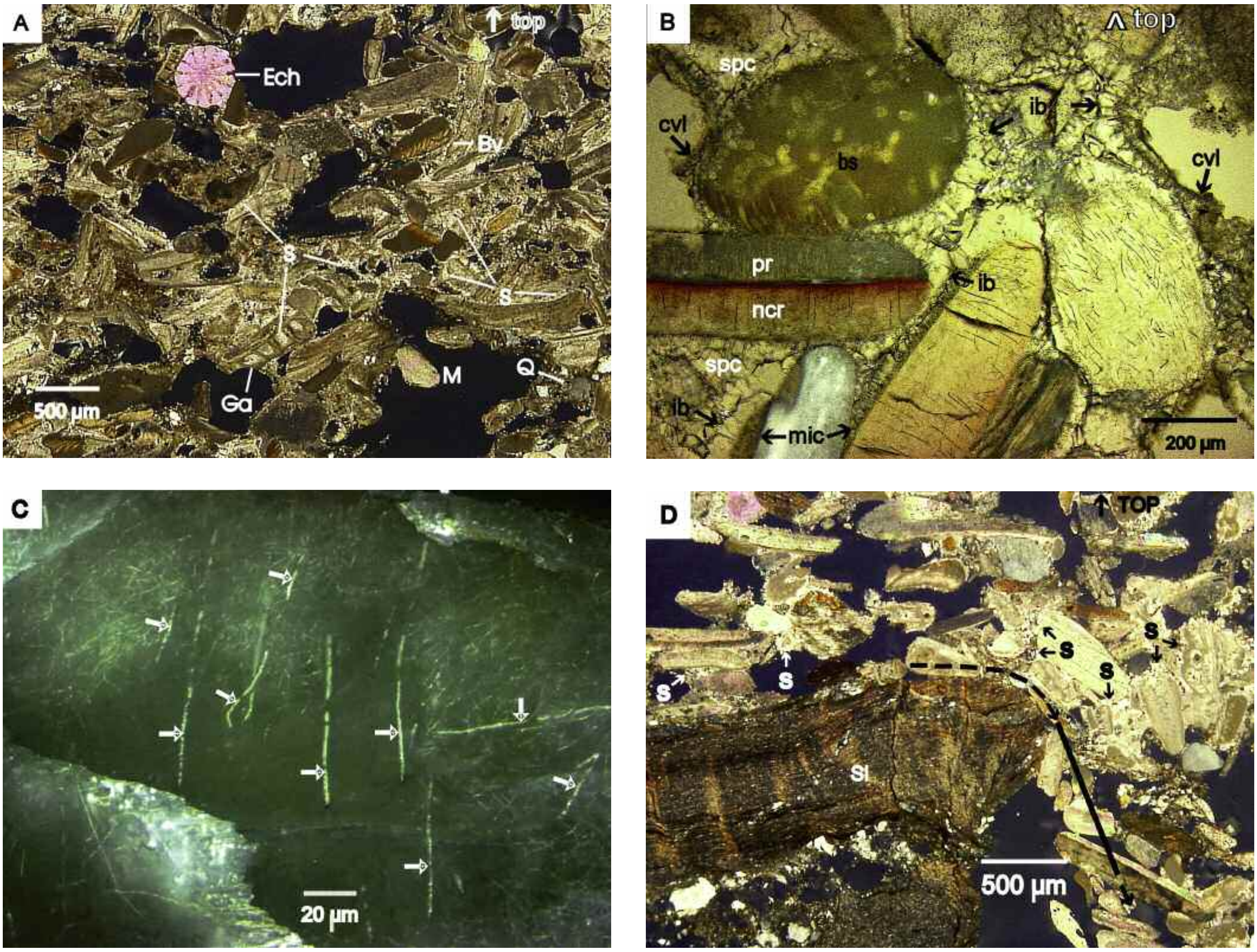

Figure 11. *(**a**) Loc. BR10A: thin section, transmitted light: crossed polarisers; showing porous beachrock fabric composed partially of spar-cemented (bright areas, arrowed S) fragments, mainly comminuted bivalve shells (Bv), sub-parallel to bedding plane, with occasional gastropod (Ga) (infilled with calcite spar), echinoid spine (Ech) and sub-rounded quartz (Q) and mica (M) grains. (top of bedding-orientated thin section arrowed). (**b**) Loc.10B: polished section, reflected light: partially crossed polarisers; Automontage showing relatively unaltered prismatic (pr) and nacreous (ncr) structure in section of bivalve shell, bored/eroded shell grain (bs), bladed/equant calcite crystals (spc) with interlocking polygonal boundaries (ib) between grains, possible micrite (mic) and further infilling in cavities coating earlier calcite (cvl). (top of bedding- orientated thin section arrowed). (**c**) Loc. 10B: polished section, reflected light: partially crossed polarisers; Automontage; showing possible algal or bacterial micro-borings ~2 µm in diameter (arrowed) in shell fragment. (**d**) Loc. BR10A: thin section, transmitted light: crossed polarisers; showing evidence of interrupted flow (arrowed dashed and solid lines,) under gravity, of small grains over the slate granule (Sl), cemented in descent by calcite spar (S). (top of bedding-orientated thin section arrowed).*

Harlyn beach and Little Cove experienced a number of sea level transgression/regression phases during the Holocene and that meteoric $CaCO_3$ and other mineral-rich fluids originating from the Trevose isthmus dune field invaded the beach fabric in the phreatic zone on a number of occasions. Preliminary observations at Daymer Bay and Rock Beach suggest a comparable history. Further work is required to (a) constrain the source of the precipitating solutions for the carbonate cement in these beachrocks, (b) confirm whether two or more cement phases occurred and (c) establish a chronology for the formation of the deposits.

The present study indicates that the Harlyn beachrock would appear to be of different origin to the both the North Uist micritic high-Mg calcite and aragonite cemented beachrocks (Kneale and Viles, 2000), which are associated with aeolianites and cemented beach crusts, and the acicular aragonite cemented beachrock in Clew Bay, Ireland (Sellwood, 1994). There are some similarities between the setting and mineralogy of the low-Mg calcite Harlyn beachrock and the low-Mg calcite beachrock developed in the Corrubedo Complex, Ria de Arousa, NW Spain (Rey *et al.*, 2004). However, in Ria de Arousa the principal sediment source for the beachrock is fluviatile material whereas in Harlyn the source is littoral sand. In Ria de Arousa there is also evidence of an on-going cycle of events involving calcite cement formation in the vadose zone, later wave modelling of exposed beachrock, reburial and re-deposition of new carbonate cements promoted by micro-organisms and algae. Whether or not this chain of events occurs, or has occurred, in the Harlyn beachrock and in the Camel Estuary deposits is debatable.

The cluster of beachrock occurrences in Mother Ivey's Bay, Harlyn Bay and in the Camel Estuary offers an opportunity for further more detailed work on the sedimentology and lithology of the beaches and associated dune environments in which they are found. Geochemical analyses of the beachrock sediments and cements may assist in setting a chronology and environmental history for these deposits and thereby help shed further light on the evolution of this part of the north Cornwall coastline.

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