Updated interpretations of Late Quaternary sections in West Cornwall resulting from winter storms in recent past

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The unprecedented series of winter storms of 2013/2014 removed rock armour sea defences, cut new sections and scoured beach sands from the adjacent shore platforms as well as breaching of coastal defences, cliff falls and flooding of coastal areas.Quaternary coastal sections at Godrevy (SSSI) and Gunwalloe Fishing Cove have been revisited and a Holocene clay deposit at Kennack Sands is documented for the first time. The bedrock behind the Quaternary section at Godrevy, is increasingly being revealed following the winter storms with new exposuresof the fossil cliffat the northern and southern ends of this important Quaternary site and its landward configuration is shown to be of significant importance in the development of the section. It is argued that the cementation of the sandrock (aeolianite) prominent in Godrevy North, extended much further south to Godrevy Rocks prior to its current decalcified condition. Stratified slope sands and thinner slate-rich layers have been identified on the northern flank of the Magow Rocks immediately above the bedrock. These are either coeval with the "littoral" sands above the raised beach further north or older than both.

At Gunwalloe Fishing Cove, the total collapse of a previously described Quaternary section to the north during the 2013/2014 storms has been compensated by the exposure of a new Quaternary section to the south, comprising raised beach, stratified colluvial slope sands and upper periglacial head. Scouring of beach shingle seawards during winter storms has shown that the particularly steep beach profile here results from the frontal erosion of the former shore platform by wave quarrying and abrasion during the Post-Glacial sea level rise.

Scouring of beach sands at Kennack Sands during storms has revealed the full extent of the Holocene clay beneath, which is interpreted as a lagoonal deposit formed behind the dunes as they moved landward during the Post-Glacial sea level rise. They are similar in origin to the Praa Sands peat and the submerged forest at Mounts Bay further west.

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Introduction

The South-West has always been prone to the effects of Atlantic depressions, causing heavy rainfall, breaching of coastal defences, removal of beach sand, cliff falls and flooding of coastal areas. In January/February 2014 the effects of an unprecedented series of Atlantic depressions and swells were particularly severe (Poate *et al.*, 2014; Scott *et al.*, 2016 and Masselink *et al.*, 2016). This paper revisits/reinterprets Quaternary coastal sections at Godrevy (SSSI) and Gunwalloe Fishing Cove, initially described more than 40 years ago and documents, for the first time, a Holocene clay deposit at Kennack Sands that has been gradually revealed by reported storm activity over the last 20 years (Fig. 1).

Figure 1. *Location of three sites discussed in the paper.*

Godrevy

This ~ 1 km long coastal Pleistocene section forms the northern margin of St Ives Bay (Figs 1, 2) which is separated from the central part of the bay by the mouth of the 13 km long Red River. This north-west facing coast is the most exposed part of St Ives Bay (Masselink *et al.*, 2016). The bedrock comprises

Figure 2. *Oblique aerial photograph of Godrevy looking north, showing coastal section and behind bedrock ridges, mapped head basins and in foreground Holocene dunes and Red River mouth. Roman numerals show location of lithofacies logs. Photograph F12/149 1987, Historic Environment Record, Cornwall Council.*

slates and sandstones, of the Porthtowan Formation (Leveridge *et al.*, 1990). It is characterised by three ridges and two mapped 'head basins' (BGS Sheet 351/358, 1984) and not a single basin as shown in published 2-D cross-sections in Hosking and Pisarski (1964), Scourse (1996) and Scourse and Furze (1999). These ridges and basins with a NE to SW trend are reflected to some extent in the relief of the shore platform immediately offshore with rocky platforms adjacent to ridges and lower lying sandy beaches seaward of the basins. With its impressive exposures of interglacial littoral deposits, overlying periglacial 'head' and Holocene dune sands that have received considerable attention over the past two centuries (De La Beche, 1839; Ussher, 1879; Prestwich, 1892), Godrevy is considered one of the most important Late Quaternary sites in south-west England (Campbell *et al.*, 1998; Bell and Brown, 2008).

The generalised accepted Quaternary section (James, 1975a; Campbell *et al.*, 1998; Scourse and Furze, 1999) is summarised in the vertical lithofacies logs for Godrevy in Figure 3 and is shown in Table 1.

Units 1 and 2 form the stratotype of the Godrevy Formation of Scourse (1996), now the Godrevy Member of the Penwith Formation (Campbell *et al.*, 1999).

The Godrevy section between Godrevy Point and Magow Rocks has long been subject to coastal erosion. Both Ussher (1879) and Prestwich (1892) drew attention to an isolated outlier of 'head' 70 yards seaward of the then cliff line at Godrevy Rocks. This pinnacle/stack had disappeared by the early twentieth century, (Whitley, 1905). Zawns on Godrevy Rocks reef, trending more or less perpendicular to the coastline have facilitated the development of pronounced gullies in the soft cliffs, particularly in the section north of the Godrevy Farm access road, accentuating the threat to a substantial length of road accessing the Godrevy Cove/Head National Trust car parks and Godrevy Farm between the location of vertical lithofacies logs II and III (Fig. 3).This is now located close (< 10 m in one area) to the cliffs of the coastal section compared to 20 m in 1975. The storms of 2013/14 further exacerbated the situation, undercutting access steps to the foreshore above Godrevy Rocks. The coastal retreat in the area is increasingly exposing the complex bedrock configuration landward of this historic coastal section.

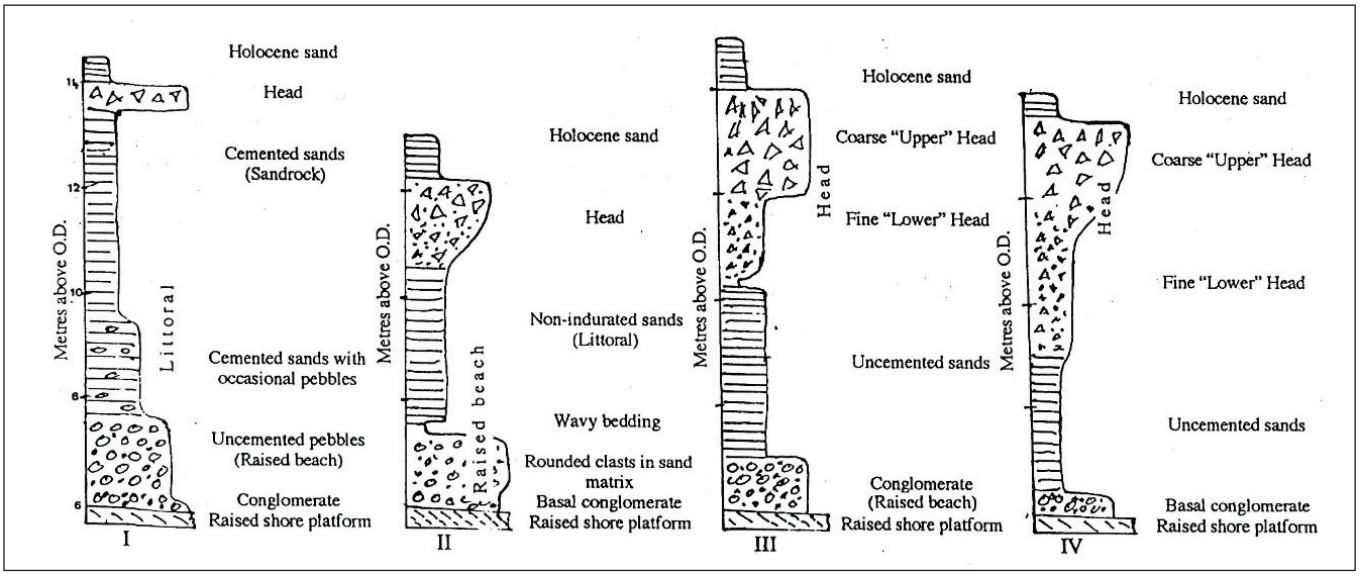

Figure 3. *Vertical lithofacies logs I-IV at Godrevy.*

	Lithostratigraphical descriptions	Revised correlation (Bowen, 1999)
5.	Soil	
4.	Holocene sand	
3.	Varying facies of head	St Loy member of the Penwith Formation, (Bowen, 1999).
2.	Cemented to uncemented sands with local clay lenses	Godrevy Member of the Penwith Formation (Bowen, 1999).
1.	Basal pebbles and sands, in places cemented by iron (III) and manganese (IV) oxides	Godrevy Member of the Penwith Formation (Bowen, 1999).
SHORE PLATFORM	Folded slates and sandstones	Porthtowan Formation (Leveridge *et al.*, 1990)

Table 1. *Godrevy: Lithostratigraphic units.*

Godrevy North

The northern 130 m long section at Godrevy is dominated by over 4 m thick $CaCO_3$ cemented sands (sandrock) of Unit 2. Like other examples of sandrock in the Southwest, Unit 2 is penetrated by vertical pipes, the palaeokarst of Moraweika (1993, 1994, 1997). The sands themselves exhibit large scale cross-bedding and have been interpreted by James (1975a) and Scourse (1996) as aeolian. Located on the northern horn of St Ives Bay, the sandrock aeolian facies with landward dips probably originated as cliff front (Clemmensen, 1997) or echo dunes (Tsoar, 2011), with sand being blown up against the cliff at Godrevy North from an increasingly exposed beach to the west as sea level began to fall at the start of the Devensian stage fall in sea level.

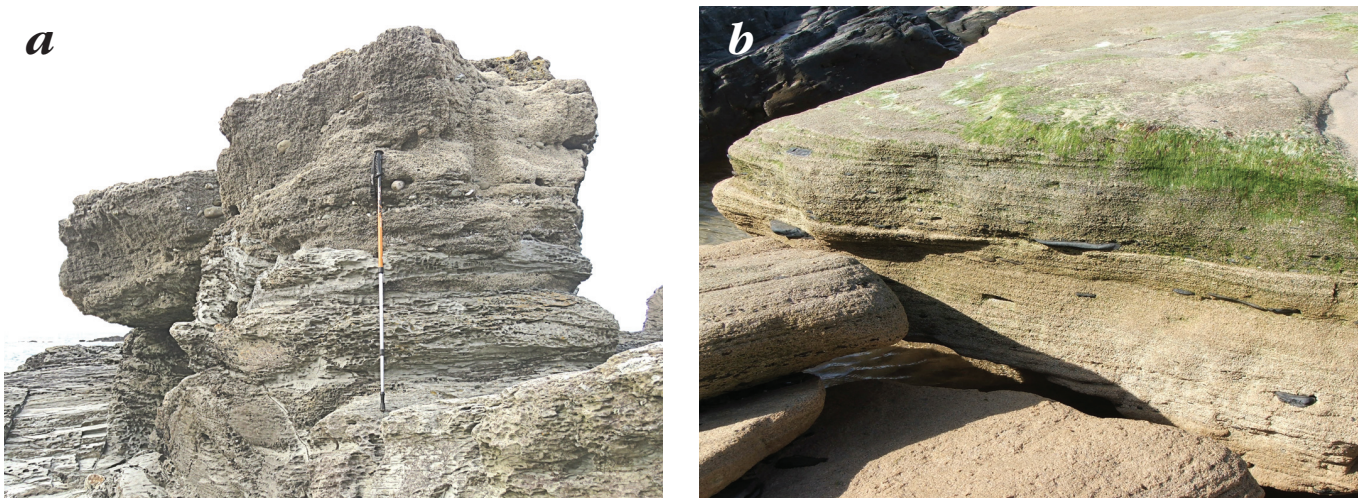

Figure 4. *Godrevy outlier: (**a**) close up of outlier, consisting of cemented sandrock with coarse sand unit and occasional well rounded pebbles overlying honeycomb weathered bedrock. This unit is the equivalent of the lower sandrock, unit 2) in the cliffs overlying the basal raised beach pebbles which are seen in Figure 5. Occasional complete shells of* Patella vulgatus *and* Mytilus *sp. occur within this sediment. Vertical scale 1.25 m; (**b**) Harlyn Bay beach rock analogue. Vertical scale 1 m.*

The lower metre, with sharp contact with the underlying conglomeratic raised beach, differs in being finer grained and contains rounded slate clasts. This lower facies is seen again on the shore platform in the well-known outlier (Fig. 4a), first referred to as a 'cromlech' by Boase (1832) and later illustrated by Ussher (1879). Differentiating this lower sandrock facies from the overlying aeolian sands above, James (1975a) interpreted it as marine. Scourse *et al.*, (1999) noted the absence of talitrid sandhopper trace fossils, characteristic of a back shore or frontal dune setting, in this Godrevy sandrock section and suggested a foreshore environment of deposition. Subsequently the authors have identified an upper foreshore analogue (Fig. 4b) preserved in the beach rock of Harlyn Bay and documented by Howie (2009).

During the 2014 storms, dramatic cliff falls affected the sandrock at Godrevy North as had previous storms in 1975 when James (1975a) discussed new evidence explaining the formation of piping palaeokarst (near vertical pipes in sandrock (aeolianite) following the exposure of vertical pipes filled with decalcified sand. Only cross-sections of *empty* pipes were available prior to the storms in 1974, but following the falls of large sandrock blocks, pipes filled with brown decalcified sands with grade size and petrology almost identical to the cemented sandrock were revealed. It was also noted, later confirmed by Walsh and Morawiecka, (1999) that the dark uncemented sands found in the collapsed pipes also formed a surface layer between the cemented sandrock and the overlying head, comprising clast supported slate breccias. Following the 2014 storms, the formerly vegetated lateral contact of the sandrock with the bedrock cliffs to the north, and its upper surface have been exposed. It is noticeable that the sandrock is increasingly decalcified as the fossil cliff is approached (Fig. 5). Located on the northern horn of St Ives Bay, the sandrock aeolian facies with landward dips probably originated as cliff front (Clemmensen, 1997) or echo dunes (Tsoar, 2001), with sand being blown up against the cliff at Godrevy North from an increasingly exposed beach to the west as sea level began to fall at the start of the Devensian stage fall in sea level.

The upper layer of decalcified sand between the cemented sandrock and overlying head can also be seen to be laterally more extensive, onlapping the bedrock cliffs to the north. Throughout the N–S trending Godrevy North section frost shattered bedrock has been increasingly exposed behind the sandrock in the upper parts of the cliffs and there are indications that the sandrock/bedrock contact is here too characterised by decalcification, presumably intensifying instability in the sandrock cliffs.

Godrevy Cove and Rocks

Godrevy Cove lies south of Godrevy North, where the coastline changes from a N–S to a NW–SE direction. Much of this sector, below the main NT car park, is characterised by degraded cliffs, covered with vegetation and does not appear to have been affected by the 2014 storms. Sandwiched between the rocky intertidal-supratidal rocky reefs of The Cleaders and Godrevy Rocks (Fig. 2) Godrevy Cove is fronted seawards by a SW sloping beach that is separated from the former shore platform with its raised beach deposits by a 1–2 m mini-scarp. Sections are only exposed at the northern and southern ends (Fig. 3, vertical lithofacies logs II and III). In the vicinity of section II a local bedrock buttress is seen in the cliffs and the head of unit 3 comprises slaty clast supported breccia. Isolated remnants of sandrock *with piping palaeokarst* may still be found at the northern end of Godrevy Cove but Unit 2 here is generally characterised by uncemented sands lacking any comminuted shell with 2–5 cm thick wavy sandy clay beds at the junction with Unit I.

The southern end of Godrevy Cove coincides with the seaward extension of the Godrevy Farm ridge. Here the access path down to Godrevy Cove cuts obliquely through the Quaternary sequence with frost shattered bedrock at the top, indicating the proximity of the ridge, before passing through Unit 2 sands towards the bottom of the path. These are again overlain by a metre of slaty clast supported breccia (Fig. 3, log III; Crisp *et al.*, 2001, fig. 2).

At the northern end of Godrevy Rocks, the coastline resumes a more N–S trend. This section, lying between the Godrevy Farm ridge in the north and the Magow/Godrevy Towans ridge in the south, contains the thickest (up to 4 m) head deposits (Unit 3) and the lowest part of the former shore platform throughout the whole Godrevy section (4.69 m O.D. James, 2001–2002). In this low part of the platform, the Fe (III) and Mn (IV) oxide cementation of the overlying raised beach conglomerates and sands is particularly well-developed and it is probably not a coincidence that the "erratic" basic rocks at Godrevy Rocks described as 'greenstone' by Robson, (1944) and as dolerite by Hosking and Pisarski (1964) also occur here. It should be noted that these I m sized 'erratics' were originally 2–3 m in dimension until reduced in size by mining students 50 years ago. Whether these boulders and other smaller exotic rock types elsewhere on the raised shore platform in Unit 1 were derived from further along the north Cornish coast or from across the Bristol Channel is a moot point, as there is increasing evidence of glacial activity in the Celtic Sea (Scourse, 1996) and the Bristol Channel (Gibbard *et al.*, 2017).

The raised beach (Unit I) is overlain by 2–3 m of unconsolidated sands (Unit 2). These appear bedded (dm scale). Clay bands have been recorded by James (1994) in the upper interval below Unit 3 which is composed of slate and vein-quartz rich matrix supported head. The upper head (<3 m thick) is much coarser than the lower head and contains numerous clasts of vertically oriented angular to sub-rounded vein-quartz clasts. James (2004) regarded the latter as probable polygonal permafrost structures preserved in sections. The contact between Units 2 and 3 appears relatively horizontal overall, but detailed examination shows local erosional hollows (metre scale), filled with head in the upper surface of Unit 2 sands, and injection sills of Unit 2 sands within the head. The latter probably result from post-depositional loading. The erosional hollows have been discussed in terms of possible 'frost wedges' (James, 2004, *op. cit.*). However, it is advanced here, that they may be relics of piping palaeokarst, similar to that exposed at Godrevy North (Fig. 5).

Figure 5. *Close-up of recent N–S exposure of decalcified sands at bedrock/sandrock contact. Remnants of palaeokarstic piping are seen in the south, overlain by I m thick decalcified sandrock beneath periglacial head. A limited exposure of the basal pebble raised beach, Unit 1, may be seen in the centre of the figure just above the platform with collapsed blocks of sandrock.*

Previously, little attention has been paid to the Quaternary section at the southern endof Godrevy Rocks where the bedrock rises from the former shore platform and merges with the Magow Rocks–Godrevy Towan ridge, probably because it is higher in the cliffs and less accessible. The bedrock in the area is noticeably paler and more weathered/altered than elsewhere as Hosking and Pisarski (1964) and James (1975a) noted. This appearance has previously been attributed to the near surface presence of granite. Possible associated kaolinisation and mineralisation has beenconfirmed (R.K. Shail, *pers. comm.*, 2016) more recently. Significantly the contemporary shore platform in this area is lower than the intertidal Godrevy Rocks reef immediately to the north and covered by beach sand, due to its lesser resistance to erosion thus it is speculated that this southern area was the first to be eroded by the Post-Glacial rise in sea level.

Late Quaternary exposures, (Hosking and Pisarski, 1964; Scourse, 1996; Campbell *et al.*, 1999) show the uncemented sands (unit 2) wedging out southwards against the rising slope (Fig. 3). A re-examination indicates the presence of a previously unrecognised unit of stratified sands and thinner slate-rich layers immediately above the bedrock *thickening* up slope (Fig. 6).

The sediment–bedrock junction, lies midway between Godrevy Rocks and Magow Rocks and corresponds to the boundary between the cultivated fields of Godrevy Farm and rough ground of Godrevy Towans (Fig. 2). In cross-section it is relatively sharp and steep. Initially sands and slate fragments derived from upslope bedrock infilled local steep scarps created

Figure 6. *Magow Rocks section, showing newly identified wedge of stratified sands above pale coloured altered bedrock.These are overlain by reddish stony periglacial head, capped by Holocene dune sands. The total thickness of cliffs including superficial deposits above bedrock is 15–20 m.*

by the erosion of vertically-fractured bedrock. This allowed overlying sands to flow further downslope. This stratified sand unit is overlain by a head unit that thickens downslope and forms Unit 3 of Godrevy Rocks. Its lateral relationship with the sands of Unit 2 at Godrevy Rocks to the north is currently obscured. Whether it underlies or is coeval with Unit 2 of Godrevy Rocks is not clear.

Gunwalloe Fishing Cove

Gunwalloe Fishing Cove (GFC) lies on the eastern margin of Mount's Bay where the coastline turns southwards towards the Lizard Point, 12 km further south (Fig. 1).

It forms the southern end of the NW–SE trending coastline, stretching 4 km from Porthleven through Loe Bar to GFC (Fig. 1) and is exposed to the dominant SW winds, waves, swell and storms associated with Atlantic depressions. Storm waves overwhelming the Porthleven clock tower are iconic in the national and international media, and their effect on Loe Bar, which dams the River Cober, 1.8 km south-west, has received considerable attention (Spalding, 2015, Almeida *et al*, 2015). The GFC section (James 1975b) is re-examined and divided into a northern and southern section. The bedrock throughout both sections comprises slates and sandstones of the Devonian Portscatho Formation with a regional easterly dip.

Gunwalloe Fishing Cove North

This N–S trending section is backed by cliffs which increase in height from less than 20 m at the southern end to more than 40 m northwards. James (1975b), surveyed the notch/shore platform junction at 10.9 m O.D. with a maximum platform width of *c.*30 m. It is fronted seaward by a relatively steep dipping (8°–10°) flint rich shingle beach *c.*90 m wide that absorbs much of the energy from waves and swell arriving perpendicular to the shoreline. As a result, the cliffs normally only suffer marine erosion during the highest Spring tides and storms (see Earlie *et al.*, 2018). Since James (1975b) documented this northern stretch, the thickest section that he described, located some 30 m north of the slipway at the mouth of the cove has been lost (Fig. 7a, b).

Between this collapsed section and the GFC slipway, new exposures of the raised shore platform and overlying raised beach (~ 2 m thick) have been revealed. The latter, comprise locally derived tabular boulders and rounded cobbles within a manganese oxide (IV) cemented coarse sand matrix. In the lost section, which extended to within a metre of the cliff top, the basal cemented raised beach was overlain by 15 m of alternating coarse and fine-grained sands and were capped by

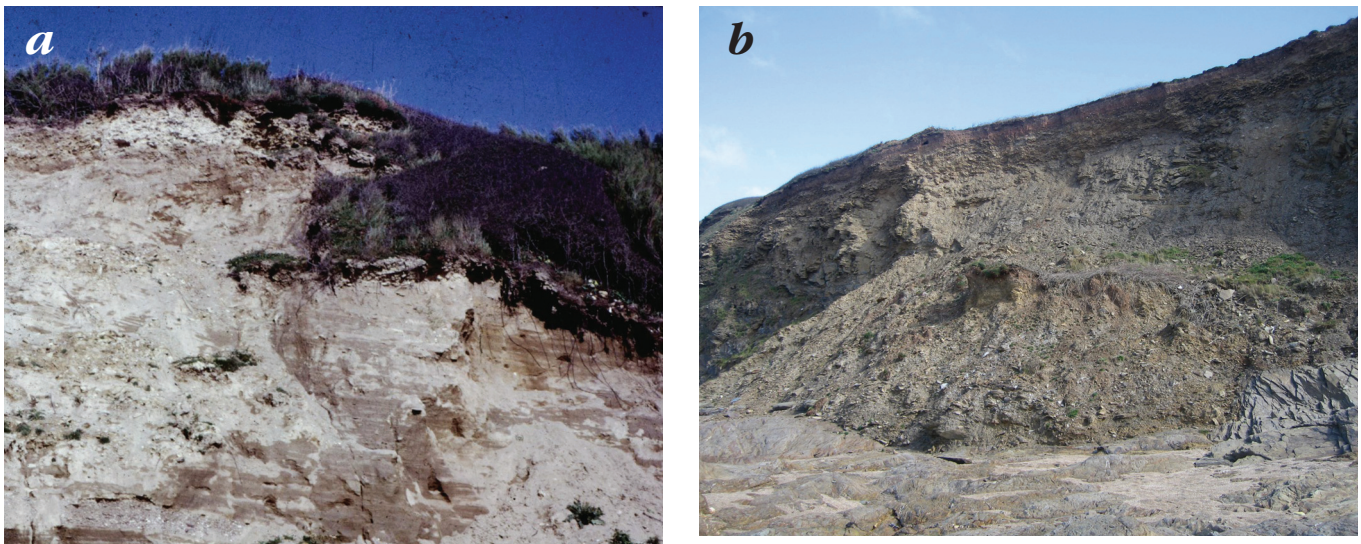

Figure 7. *Gunwalloe Fishing Cove north: (**a**) 1975 exposure showing the vertical lithofacies units above the basal iron and manganese oxide cemented raised beach through gravel and sand units to thin head unit. Total thickness above the basal shore platform ~ 20 m; (**b**) The total collapse of the section (Fig.7a) following 2014 storms.*

Figure 8. *Storm scouring of GFC flint-rich beach: (**a**) 'normal"' shingle beach; (**b**) beach scouring during storm of February, 2014.*

a 1 m thick slate breccia. These sands, with a 12° seaward dip, were interpreted as former aeolian sands, re-deposited down slope by subsequent slope processes.

During storms in November 2004 and February 2014, the flint rich beach gravels were completely scoured away, revealing a seaward dipping bedrock slope beneath (Fig. 8a, b). It is suggested that the former shore platform was more extensive with an average dip of 6° (James, 1994). This has been further degraded/steepened to 10° by wave quarrying and abrasion during the Post-Glacial sea level rise. Earlie *et al.* (2018) also commented upon the steeper slopes (10°) in the area around Porthleven three kilometres to the northwest of GFC in comparison with lower angle slopes at Godrevy on the north coast in their discussion of 'The role of beach morphology on coastal cliff erosion under extreme waves'.

Gunwalloe Fishing Cove South

This section extends from the slipway to Baulk Head and trends north-south. The cliff tops range from 15 m O.D near the slipway to 25 m O.D in the immediate area of Baulk Head. Due

Figure 9. *GFC South with waves from the south impacting the this N–S trending sector. The palaeo-embayment filled with head is clearly seen between the pill box (left) and Baulk Head (right).*

to the N–S orientation, the SW directed waves and swell directly impact the coast here (Fig. 9). A small bedrock headland, topped by a WW2 pill-box (now converted into a private viewing area with a prominent flag pole), subdivides the Quaternary section here into two.

The subsection immediately south of the slipway consists of slaty bedrock cliffs behind a 10.8 m O.D. raised shore platform some 10 m wide. The raised shore platform is now separated from the modern beach by a mini-scarp, 1–2 m high. The former platform is overlain by iron and manganese cemented coarse sand to granule grain size raised beach which is notable for the number and size (2 m long axis) of locally derived tabular local bedrock boulders. At the southern end of this section where it abuts against the local promontory, the cliff derived slabs have 3–4 m long axes. The dip of these boulders is variable, ranging from horizontal to nearly vertical (Fig. 10a). There is clear evidence that some were derived from the underlying shore platform. Wave quarried sockets (Knight and Burningham, 2011) filled with raised beach material are exposed along the landward dipping bedrock strike (Fig. 10b). Toppling failure of the landward dipping alternating sandstones and slates in the cliffs behind almost certainly produced others, particularly those on the north side of the pill-box promontory (Fig. 10c). Similar processes are currently observed on the modern beach below this promontory and on the raised platform north of Baulk Head.

Overlying the cemented raised beach, south of the slipway at GFC South, there are exposures of coarse beach sand interbedded with slate lenses, in turn overlain by colluvial slate breccias, derived from the nearby fossil cliff (Fig. 10d). These deposits are similar to those described in the original GFC North section by James (1975b) which has recently collapsed (Fig. 7a, b).

The sub-section south of the WW2 pill-box is characterised by a marked palaeo-embayment mapped by the British Geological Survey (Sheet 359, 1975 reprint) as 'head'. It has been subject to rapid coastal erosion especially below the pill-box. Consequently, in 1993/94, a concrete sea wall, some 40 m long and 3–4 m high, was constructed privately to protect the residence above. As part of the seawall construction, two rows, (~ 15 m in length), of granite rock armour were added to defend its southern end (Fig. 11a, b). Over the intervening years, these rock armour blocks have been completely

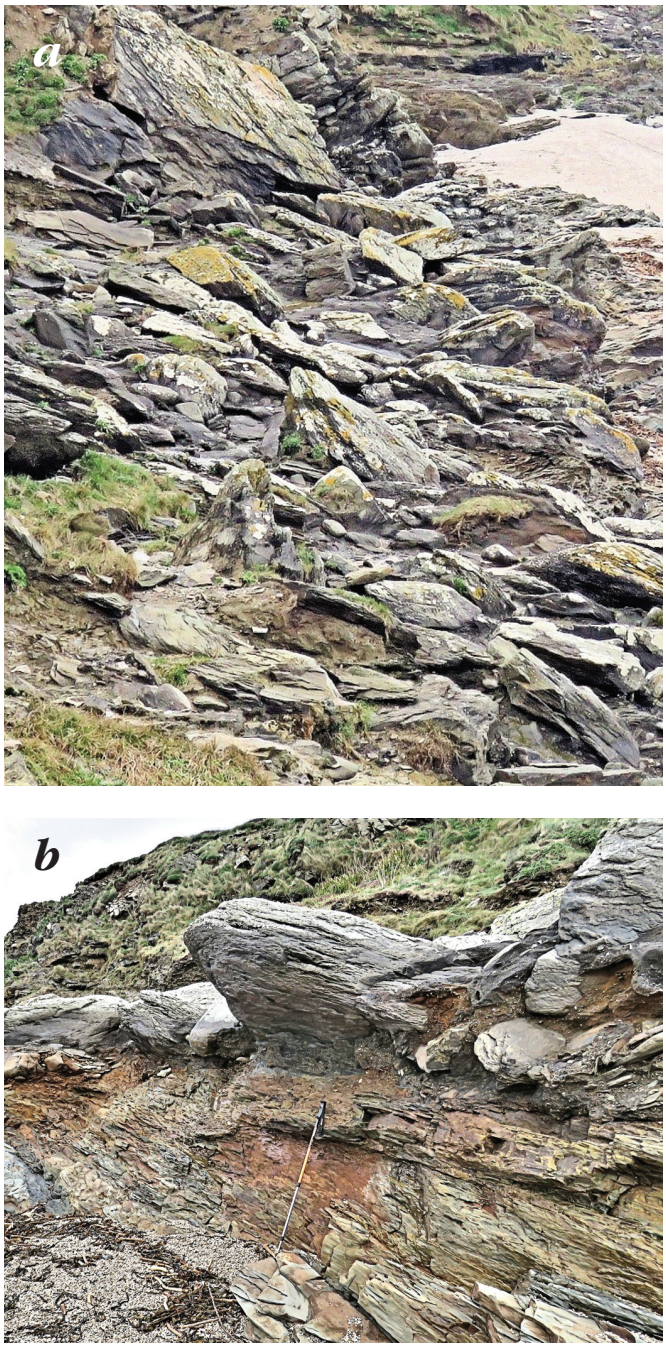

Figure 10. *GFC South between slipway and pill box: (**a**) raised beach and tabular boulders.Lateral scale 30 m. Boulder size 0.5–2 m; (**b**) wave quarried sockets on either side of landward dipping bedrock, highlighted by trekking pole, scale 1.25 m; (**c**) toppled bedrock slab on north side of pill box promontory. Scale as for (**b**); (**d**) coarse beach sand inter-bedded with slate lenses overlain by colluvial slate breccias scale 0.5 m.*

removed and transported by storms as much as 15–20 m northwards onto the contemporary beach below. By combining photographic data from the1994–1997 ecological surveys (Liz McDonnell, personal communication) with our own 2001–2016 observations, it is clear that the storms of 2004 and 2014 were principally responsible for the removal of the rock armour.

As a result, a new Quaternary section (Fig. 12, Table 2) has been exposed, comprising:

Figure 11. *GFC South between pill box and Baulk Head: (**a**) showing progressive removal of rock armour between 2001 and 2013 (view in 2001); (**b**) showing progressive removal of rock armour between 2001 and 2013 (view in 2013).*

Figure 12. *New section of iron and manganese oxide cemented basal raised beach overlain by stratified sand and gravel and soliflucted head, after total removal of rock armour by 2014 storms. Scale 6 m thickness above bedrock platform.*

Lithostratigraphical units/thickness	Lithostratigraphical description	Revised Correlation (Bowen, 1999)
Unit 3 2.5 m	Head (thin unit at base). Fine matrix supported angular clasts displaying clear fabric.	St Loy member of the Penwith Formation, (Bowen, 1999).
2.6 m	Stratified coarse sand and gravel, identified as a slope deposit.	
0.7 m	Uncemented sands with angular and rounded slate discoids at the top.	
Unit 1 1.5 m	Fe/Mn cemented raised beach sands with angular and rounded discoidal boulders overlying the Pleistocene shore platform.	Godrevy Member of the Penwith Formation (Bowen, 1999).
SHORE PLATFORM	Devonian slates and sandstones.	Portscatho Formation

Table 2. *Gunwalloe Fishing Cove south: Lithostratigraphic units.*

As in the northern subsection, this indurated basal beach contains bedrock clasts but here they are smaller (0.5 m) than those in the northern subsection (Fig. 10a) with rounded-angular edges and less frequent. The density and size of boulders increases southwards toward the bedrock cliffs of Baulk Head. The stratified alternating coarse sands and gravels dip seaward and are interpreted as slope deposits derived from the landward cliffs and slopes above (Fig. 10c). The overlying matrix supported head can be followed discontinuously southwards towards Baulk Head. Here, a northward thinning unit of bedrock clasts, derived from Baulk Head is intercalated within it.

Steep-sided coves are currently being incised into the bedrock cliffs of Baulk Head and immediately south. Their development appears to be facilitated by the erosion of faults perpendicular to the coast. It is suggested that the palaeo-embayment in GFC South, described here, originated in the same way during an earlier interglacial. In GFC South, the faults are commonly marked by tufaceous seeps.

Kennack Sands

Kennack Sands lies in a large embayment on the south side of the Lizard Peninsula between the Most Southerly Point and Black Head (Fig. 13) Kennack Sands are the type section for the Kennack Gneiss Group (Floyd *et al.*, 1993), a commingled magma intrusion at the thrust junction of the Goonhilly and basal nappes of the Lizard Ophiolite Complex. The gneisses are known to decompose and weather much more easily than the adjacent serpentinites and it is highly likely that they extend farther seaward into the offshore embayment (Flett and Hill, 1912). The Quaternary sediments in the area have received little attention to date. There are local anecdotal tales of clay with treeremainsbeneath the beach sand. More systematic observations since 1990 after storms have revealed its nature, extent and stratigraphic relations.

Kennack Sands is divided by a ridge of serpentinitic rocks, which extends seawards as a prominent reef known as the Caervarracks, into two sandy beaches, referred to here as Western and Eastern beaches. These gently sloping beaches, with wide (100+ m) intertidal zones, together, form the largest sandy beach on the Lizard Peninsula.

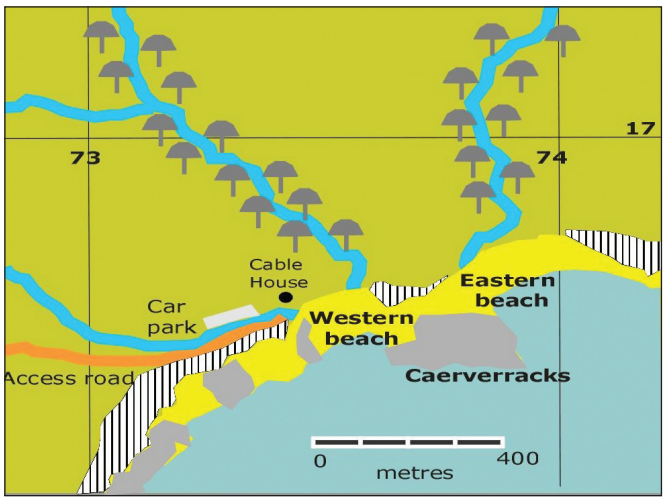

Figure 13. *Location map of Kennack Sands showing Western and Eastern Beaches.*

Western Beach

This beach, closest to the only access road, is formed at the mouth of two valleys (Fig. 13) incised into the underlying Kennack Gneiss. Since 1885 the beach has acted as the landfall for submarine cables from the Channel Islands and Spain, which were then routed to the nearby village of Kuggar (Johns, 1999). The cables were entrenched into beach sands (Fig. 14a). Subsequent storms have scoured the beach sands, frequently exposing the cables lying in a stiff grey brown clay. The full extent of the clay was revealed (Fig. 14b) after the 2014 severe storms. It underlies the entire beach and extended into the lower parts of both valleys. On its margins it can be seen resting on Pleistocene head charged with Kennack Gneiss debris. These are overlain by Holocene dunes. The clay itself contains reed-like leaves, wood fragments and more unusually isolated 2–5 cm rounded flint pebbles, which, once eroded from the clay, form a significant lithological component of the modern shingle.

Eastern Beach

This beach is formed at the mouth of a valley that developed along the arcuate junction between the Crousa/Trelan gabbros and serpentinised peridotites. The beach is separated from the main deeply incised valley behind by a degrading WW2 anti-tank wall, against which a steeply sloping stormbeach is banked (Fig. 15).

Matrix supported serpentinitic head deposits thicken eastwards down slope from the ridge separating East and West Kennack. These are overlain by 1+ m of stratified loess and well-developed vegetated Holocene dunes. Similarly, eastward dipping head and loess occurs farther seawards on the eastern flank of the Caervarracks in the intertidal zone. An augur hole, 2.5 m deep, in the middle of the clay exposure is considered a minimum thickness as its surface has been clearly runnelled, indicating downward erosion. A peat/palaeosol bed is occasionally exposed beneath the storm beach in front of the concrete sea wall.

In 1998, logs were found at the eastern margin of the clay where it abuts serpentinite bedrock (Bates and Scolding, 2000). They lie horizontally in the clay and hence not in growth position. The site (SW 73881662) has since been documented – as a submerged forest – in Cornwall Council's Historic Environment Record as MCO32347.

Discussion

Godrevy North and Godrevy Cove appear to be part of a relatively high bedrock dominated geomorphological unit.The Godrevy Cove section, with its thick sands of Unit 2 and relatively thin slate breccia head deposits, is interpreted as a continuation of the cliff front foreshore and dunes, seen at Godrevy North. As well as the well-known piping palaeokarst of the sandrock, additional decalcification, probably younger and controlled by the steep contacts with the bounding bedrock, has been identified at Godrevy North. Our evidence suggests that the non-cemented equivalents at Godrevy Cove and possibly further south were also formerly cemented and have been since been decalcified.

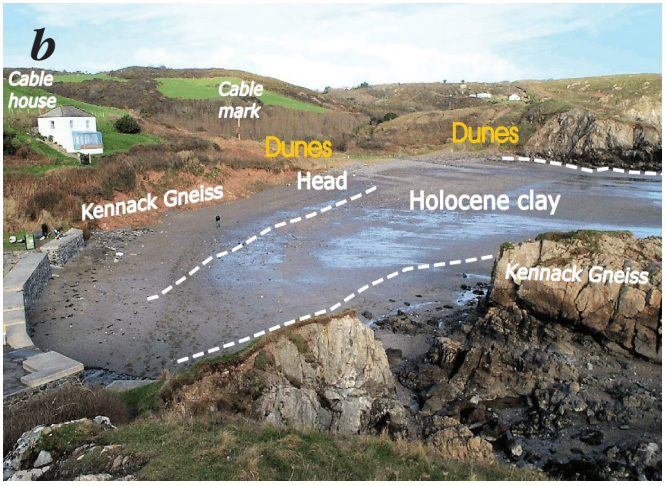

Figure 14. *Western Beach: (**a**) submarine cables to Channel Islands and Spain within Holocene clay exposed by storm beach scouring; (**b**) extent of Holocene clay on Western Beach.*

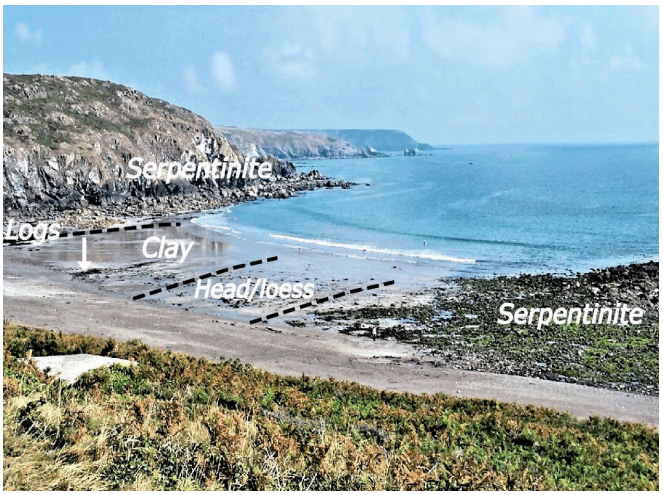

Figure 15. *Eastern Beach with serpentinite cliffs. The white arrow marks the auger site. The Holocene clay, with exposed logs, onlaps loess/head laterally and landwards.*

The prominent outlier at Godrevy North (Fig. 4a) is correlated with the basal part of Unit 2 (Fig. 3) in the adjacent cliffs. The recognition of a modern day analogue at Harlyn Bay confirms the upper foreshore environment of deposition as suggested by Scourse *et al*. (1999).

The Godrevy Rock section south to Magow rocks, with its thicker head and thinner Unit 2 sands, is regarded as the infill of a palaeo-valley, presumably a former tributary of the Red River (Fig. 2). The sands of Unit 2 are generally assumed to have been derived by deflation of former marine shelf areas to the west. The identification of stratified slope deposits south of Godrevy Rocks, either coeval or older than Unit 2, indicates that a more local source from the flanks of the Magow Rocks ridge may also have been available for mixing in this palaeo-embayment 'littoral' setting. Significantly, Hosking and Camm (1980) considered that the presence of pyrite framboids in the basal Fe/Mn cemented conglomerate of Unit 1 indicated swampy conditions prevailed in this palaeo- embayment before the deposition of the periglacial head (Unit 3).

Significant changes in the Pleistocene sections at Gunwalloe Fishing Cove since the early 1970s have largely resulted from storm wave activity, particularly in 2004 and more recently 2014. The complete removal and landward translocation of rock armour boulders by storm waves within the last 20 years indicates the vunerability of this locality to storms.That such storm waves occurred along this coast in past interglacials cannot be precluded as an explanation for the locally derived boulder rich raised beaches at both GFC North and South. Storm boulder fields are increasingly being reported from current intertidal shore platforms (Knight and Burningham, 2011; Naylor *et al*., 2016). The new section at GFC South with its raised beach, stratified colluvial slope sands, and upper head, is the best developed Late Quaternary section east of Praa Sands 9 km farther west (Scourse, 1996; Ealey,1999). The raised beaches at Gunwalloe Fishing Cove are here correlated with the Godrevy Member and are similar, in cementation and proximity to the former cliff line, to the Pendower Bed (see Campbell *et al*., 1998) in Gerrans Bay further to the east.

The Kennack Sands Holocene clay is interpreted as lagoonal deposit formed behind the dunes as they moved landward, similar in origin to the Praa Sands palaeosol (Goode and Taylor, 1988) and the submerged forest at Mounts Bay further west. The origin of the ubiquitous isolated flint pebbles is not understood; possibly a flint-rich ridge preceding burial by advancing dunes of the flints drifted into the lagoon attached to seaweed.

Conclusions

Lithostratigraphical and geomorphological evidence for the impact of the 2013–2014 winter storms is demonstrated at the three sites, Godrevy, Gunwalloe Fishing Cove (GFC) and Kennack Sands (Fig. 1). Historical evidence of Quaternary outliers indicates that in the past (pre-1850s at least), the Godrevy Quaternary section extended much further seaward. A modern day analogue from Harlyn Bay has been identified that confirms the upper shoreface environment of deposition for the sandrock outlier at Godrevy North. This coastal retreat (~100+ m) is increasingly exposing the complex bedrock configuration landward of the cliff line section and its role in the development of this historic coastal section. The most important features in the landward bedrock configuration are the fossil high standing cliff line between Godrevy North and Godrevy Cove and the well developed palaeo-valley between the Godrevy Farm and Magow Rocks ridges. There is evidence to indicate that the sandrock cementation of Godrevy North at one time was more extensive but has been increasingly decalcified southwards towards Godrevy Rocks.

The removal of the extensive Quaternary section north of Gunwalloe Fishing Cove during the 2013–2014 storms has been compensated by the exposure of a new Quaternary section in the south, comprising raised beach, stratified colluvial slope sands and upper periglacial head. The most striking feature of the sections at Godrevy and Gunwalloe Fishing Cove is the substantial thickness of aeolian sand and/or colluvial slope deposits between the formation of the raised beach deposits and the deposition of typical periglacial head. The Holocene clays of Kennack Sands are one of a series of such deposits, formed behind advancing coastal dunes during the Post-Glacial sea level rise and similar in origin to the Praa Sands peat (Goode and Taylor, 1988) and the submerged forest of Mounts Bay further west.

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References

ALMEIDA, L.P., MASSELINK, G., RUSSELL, P.E. and DAVIDSON, M.A. 2015. Observations of gravel beach dynamics during high energy wave conditions using a laser scanner. *Geomorphology,* **228**, 15–27.

BATES, R. and SCOLDING, B. 2000. *Beneath the skin of The Lizard: seven coastal walks exploring the geology of the Lizard Peninsula*. Cornwall County Council, Truro, 34pp.

BELL, M. and BROWN, A. 2008. *Southern regional review of geoarchaeology: windblown deposits*. Research Department Report Series, Report no 5-2009, English Heritage, Fort Cumberland, 93pp.

BOASE, H.S. 1832. A contribution towards a knowledge of the geology of Cornwall. *Transactions Royal Geological Society of Cornwall,* **4**, 166–474.

BOWEN, D.Q. (Ed.) 1999. A revised correlation of Quaternary Deposits in the British Isles. *Geological Society, London, Special Report,* **23**, 174pp.

BREW, D.S. 2004. *Understanding and predicting beach morphological change processes associated with the erosion of cohesive foreshores – scoping report*. Joint Defra/EA Flood and Coastal Erosion Risk Management R&D programme. Technical Report FD1915/TR.

CAMPBELL, S., HUNT., C.O., SCOURSE, J.D. and KEEN,D.H., 1988. *Quaternary of South-West England*. Geological Conservation Review Series, No. 14, Chapman and Hall, London, 439pp.

CAMPBELL, S., JAMES, H.C.L. and SCOURSE, J.D. 1999. Godrevy: Review of the site. In: Scourse, J.D. and Furze, M.F.A. (eds), *The Quaternary of West Cornwall*, Quaternary Research Association, London, Field Guide, 93-97.

CAMPBELL S., HUNT C.O., SCOURSE J.D., KEEN D.H. and CROOT D.G. 1999. Southwest England. In: BOWEN, D. Q. (Ed.), A Revised Correlation of Quaternary Deposits in the British Isles, Geological Society, London, Special Report No. 23, 174 pp.

CLEMMENSEN, L.B., LISBORG, T., FORNOS, J.J. and BROMLEY, R.G, 1997. Cliff front aeolian and colluvial deposits, Mallorca, Western Mediterranean: a record of climatic and environmental change during the last glacial period. *Bulletin, Geological Society of Denmark,* **48**, 217–232.

CRISP, G., PIRRIE, D., SHAIL, R.K. and SABIN, R.C., 2001. The Godrevy dog; early canine or lost pet? *Geoscience in South-West England,* **10**, 172–176.

DE LA BECHE, H.T. 1839. The Geology of North Cornwall and Devon and a part of Somerset. *Memoirs of the Geological Survey*, H.M.S.O., London.

EALEY, P.J., 1999. Praa Sands – realistic approach to geological conservation of a Cornish Quaternary coastal section. *Geoscience in South-West England,* **9**, 374–378.

EARLIE, C., MASSELINK, G. and RUSSELL, P. 2018. The role of beach morphology on coastal cliff erosion under extreme waves. *Earth Surface Processes and Landforms*, doi: 10.1002/esp.4308.

FLETT, J.S. and HILL, J.B. 1912. Geology of the Lizard and Meneage. *Memoirs of the Geological Survey*, HMSO, London.

FLOYD, P.A, EXLEY, C.S. and STYLES, M.P. 1993. *Igneous rocks of South West England*. Geological Conservation Review, Joint Nature Conservation Committee, Peterborough, Chapman-Hall, London, 256pp.

GIBBARD, P.L., HUGHES, P.D. and ROLFE, C.J. 2017. New insights into the late Quaternary evolution of the Bristol Channel, UK. *Journal of Quaternary Science,* **32**, 564–578.

GOODE A.J.J. and TAYLOR, 1988. Geology of the country around Penzance. *Memoirs of the British Geological Survey*, Sheets 351 and 358. England and Wales, H.M.S.O., London, 52pp.

HOSKING, K.F.G. and PISARSKI, J.B. 1964. Chemical characteristics of the cements of the Godrevy 10ft. raised beach and of certain deposition pipes in the St. Agnes Pliocene deposits. *Transactions Royal Geological Society of Cornwall,* **19**(5), 328–348.

HOWIE, F.M.P. 2009. Beachrock development along the north coast of Cornwall. *Geoscience in South-West England,* **12**, 85–94.

JAMES, H.C.L. 1975a. An examination of recently exposed Pleistocene sections at Godrevy. *Proceedings of the Ussher Society,* **3**, 299–301.

JAMES, H.C.L. 1975b. A Pleistocene section at Gunwalloe Fishing Cove, Lizard Peninsula. *Proceedings of the Ussher Society,* **3**, 294–298.

JAMES, H.C.L. 1994. *Late Quaternary coastal landforms and associated sediments of west Cornwall*. Unpublished Ph.D. Thesis, University of Reading.

JAMES, H.C.L. 2001–2002. The coastal palaeo-morphology of West Cornwall with particular reference to shore (wave-cut) platforms. *Transactions of the Royal Geological Society of Cornwall,* **22**, 121–144.

JAMES, H.C.L. 2004. Evidence for the extent of permafrost activity in south west England during the last cold stage. *Geoscience in South-West England,* **13**, 316–320.

JOHNS, C. 1999. *Kennack Sands: an archaeological assessment survey*. Cornwall County Council, Truro.

KNIGHT, J. and BURNINGHAM, A. 2011.Boulder dynamics on an Atlantic facing rock coastline, north-west Ireland. *Marine Geology,* **283**, 56–65.

LEVERIDGE, B.E., HOLDER, M.T. and GOODE, A.J.J. 1990. Geology of the country around Falmouth. *Memoirs of the British Geological Survey*, Sheet 352, England and Wales, H.M.S.O., London.

MASSELINK, G., SCOTT, T., POATE, T., RUSSELL., P., DAVIDSON, M. and CONLEY, D. 2016.The extreme 2013/2014 winter storms: hydrodynamic forcing and coastal response along the southwest coast of England. *Earth Surface Processes and Landforms,* **41**, 378–391.

MORAWIECKA, I.M. 1993. Palaeokarst phenomena in the Pleistocene raised beach formations in the South-west Peninsula of England: preliminary report. *Kras I Speleologia,* **7**, 79–93.

MORAWIECKA, I.M. 1994. *The nature and origin of palaeokarst phenomena in late-Quaternary calcareous sandrock, with special reference to the coasts of SW England and S Wales*. Unpublished PhD Thesis, University of Silesia, Poland.

MORAWIECKA, I.M. 1997. Piping karst in the raised beaches of South-west England and South Wales. *Prace Nuakowe Uniwesrsytetu Slaskiego w Katowicach* NR 1643. Wydawnictwo Uniwersytetu Slaskiego, Katowice, 111pp.

NAYLOR, A., STEPHENSON, W.J., SMITH, H.C.M., WAY, O., MENDELSSOHN, J. and COWLEY, A. 2016. Geomorphological control on boulder transport and coastal erosion before, during and after an extreme extra-tropical cyclone. *Earth Surface Processes and Landforms, 41*, 685–700.

PAZDUR, M.F., BLUSZCZ, A., PAZDUR, A. and MORAWIECKA, I.M. 1995. Radiocarbon and thermoluminescence studies of the karst pipe systems in South-West England and South Wales. *Radiocarbon,* **37**, 111–117.

POATE, T., MASSELINK, G., RUSSELL, P. and AUSTIN, M. 2014. Morphodynamic variability of high-energy macrotidal beaches. *Marine Geology,* **350**, 97–111.

PRESTWICH, J. 1892. The Raised Beaches and Head or Rubble-Drift of the South of England: their Relation to the Valley Drifts and to the Glacial Period; and on a Late Post-Glacial submergence. *Quarterly Journal of the Geological Society, London,* **48**, 263–343.

REID, C. and FLETT, J.S. 1907. Geology of the Land's End district. *Memoirs of the Geological Survey*, Sheet 351/358, England and Wales, HMSO, London

SCOTT, T., MASSELINK, G., O'HARE, T., SAULTER, A., POATE, T. and RUSSELL, P. 2016. The extreme 2013/2014 winter storms: Beach recovery along the southwest coast of England. *Marine Geology,* **382**, 224–241.

SCOURSE, J.D. 1996. The Late Pleistocene stratigraphy of North and West Cornwall. *Transactions of the Royal Geological Society of Cornwall,* **22**, 1–56.

SCOURSE, J.D. and FURZE, M.F.A. (eds) 1999. *The Quaternary of West Cornwall*. Quaternary Research Association, London, Field Guide, 223pp.

SHAIL, R.K., WETHERELT, A., COGGAN, J., WETHERELT, S.K. and WILLIAMS, D.C., 2011. Coastal Recession at Godrevy: Processes and Predictions. *Geoscience in South-West England,* **12**(4), 369 (Abstract).

SPALDING, A. 2015. *Loe Bar and the Sandhill Rustic Moth: The Biogeography, Ecology and History of a Coastal Shingle Bar*. Brill Academic Publishers, Leiden, 346pp.

TSOAR, H. 2001. Types of Aeolian Sand Dunes and Their Formation: In: BALMFORTH, N.J. and PROVENZALE, A (eds), *Geomorphological Fluid Mechanics*, Springer, Heidelberg, 403–429.

USSHER, W.A.E. 1879. *The Post-Tertiary Geology of Cornwall*. Private circulation. St. Austen and Sons, Hereford.

WALSH, P. T. 1999. Pre-Pleistocene geomorphological evolution of west Cornwall. In: Scourse, J.D. and Furze, M.F.A. (eds), *The Quaternary of West Cornwall*. Quaternary Research Association, Field Guide, 10–26.

WALSH, P.T. and MORAWIECKA, I.M. 1999. Piping palaeokarst in the Godrevy Formation. In: SCOURSE, J.D. and FURZE, M.F.A. (eds), *The Quaternary of West Cornwall*, Quaternary Research Association, Field Guide, 97–102.

WHITLEY, D.G. 1905. The Earth-Cliffs at Godrevy. *Transactions of the Royal Geological Society of Cornwall,* **13**, 135–149.