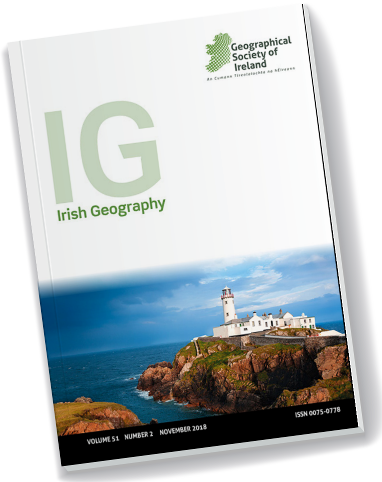

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Investigation of an Elevated Sands Unit at Tralispean Bay, South-West Ireland – Potential High-Energy Marine Event

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Abstract: A sequence of high elevation sands containing both broken and whole marine shells, as well as many mega-sized, raft-shaped boulders (1-3m across) has been discovered at Tralispean Bay, West Cork, Ireland. Ground-Penetrating Radar (GPR), ground surveying and differential GPS (dGPS) show that the sediments cover an area of c.0.75ha, reaching a maximum height of c.+18.5m ODM, with interconnected pockets of sand varying in thickness of up to 1m. Coring, lithostratigraphic study, granulometry, organics loss-on-ignition and carbonate content analyses, together with examination of micro- and macrofossils, indicate that the shelly sands were deposited rapidly, under high energy conditions. Informal interviews with local residents, as well as the extent of the sands, suggest that the deposit is not the result of human actions. Elevations reached by the sediments, the presence of mega-boulders, and other indicators make it unlikely that these sediments arose from storm activity. It is possible that they have been deposited as the result of a tsunami. The radiocarbon (AMS) date obtained places the age of such an event at 1465 AD (Cal BP 485). At present, no clear historical record has been identified of any tsunami impacts affecting the south coast of Ireland other than the Lisbon earthquake of 1755.

Keywords: *tsunami, sediments, Ireland, Lisbon, storm surge, coastal processes*

Introduction

This paper presents initial reporting of a sand-dominated sedimentary sequence (Sands Unit), containing marine shells and large boulders (megaclasts), at Tralispean Bay in West Cork, Ireland (Figure 1). The deposit extends from sea level to approximately +18.5 metres Ordnance Datum Malin (ODM) and attracted initial attention due to its altitude and unusual composition.

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Exploratory fieldwork at the site, coupled with laboratory studies of the sediments, were carried out as part of a Masters' degree research project (Cronin, 2015). Subsequently, further fieldwork has been undertaken at Tralispean, as well as reconnaissance surveys at another site further east along the south coast of Ireland where similar deposits have been found.

The evidence suggests that the sediments at Tralispean result from the impact of a large-scale coastal event, such as a mega-storm or tsunami (Dewey and Ryan, 2017; Ellis and Sherman, 2015), which occurred sometime in the 15th Century. This is the first time that marine sands of this type at such high elevations have been recorded on Ireland's coasts. These coasts are well known as being affected by large-scale storms. The significance of storms in developing coastal structures and driving process changes in Ireland, particularly on soft sedimentary coasts, is also well established (e.g., Carter and Woodroffe, 1994; Stone and Orford, 2004; Crossland *et al.*, 2005; Devoy, 1996, 2008, 2015a, 2015b; Sabatier *et al.*, 2012; O'Shea and Murphy, 2013; Wong *et al.*, 2014). Further, the scale of storminess and its impacts under future climate warming is projected as increasing (e.g., Lozano *et al.,* 2004; Gallagher *et al.,* 2014; Devoy, 2015a; Church *et al.*, 2013; National Climate Change Advisory Council, 2018). However, understanding of the extent of storm impacts on Ireland's coasts, or of the occurrence of larger scaled events, such as hurricanes or tsunami, remains to be established.

The main aims of the research were to:

1. Map the extent of the sands sequence at the site, to establish the height range and thickness of the sediments and their relationship to the underlying topography;
2. Define the stratigraphy, sedimentary characteristics and age of the Sands Unit;
3. Provide explanation of the origin and chronology of formation of the sands, and to place them in their geomorphological context;
4. Conduct wider ranging explorations on neighbouring coasts, to assess whether similar sand sedimentary sequences exist.

Study site

The study area is situated in west County Cork, Ireland, approximately 6km southwest of Skibbereen and close to Lough Hyne (Figure 1). It lies on a crenulated coast that exhibits a very strongly folded north-east to south-west trending rock structure, comprising sandstones, quartzite and slate of the West Cork Sandstone Series (Figure 2). The coast has developed as a result of submergence under the long-term impacts of postglacial sea-level rise (Devoy *et al.,* 1996, 2006, 2015a; Delaney *et al.*, 2012) and is indented with many small estuaries.

Two approximately north-south orientated river valleys bound the study site to the east and west, which connect to the higher ground inland (Figures 1 and 3). These former river valleys were glaciated and enlarged in the late Quaternary, and have acted as glacifluvial outwash channels (e.g., Lewis, 1977; Edwards and Warren, 1985; Harrison and Mighall, 2002). The eastern valley has been filled subsequently by late glacial and

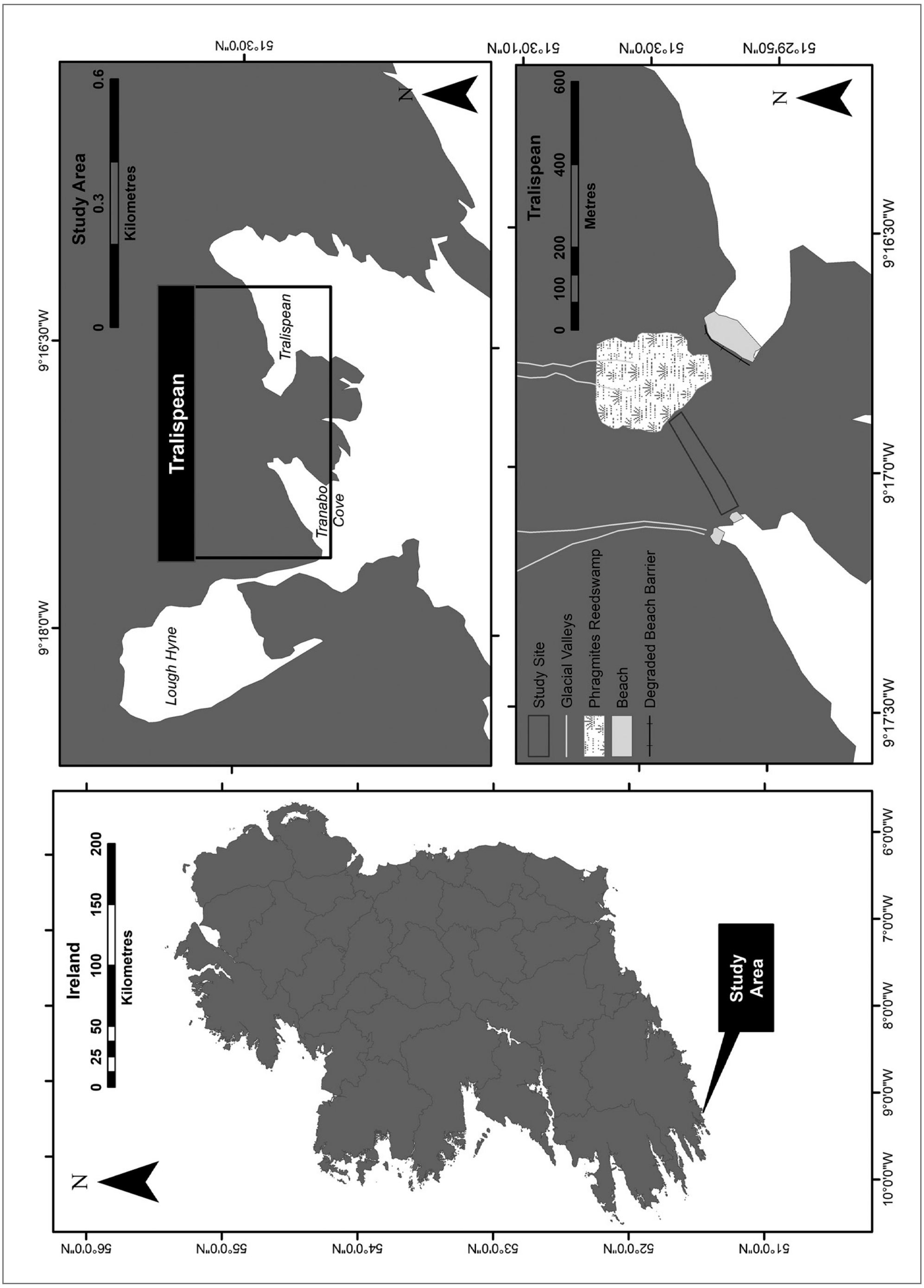

Figure 1: Location of the study site, showing the main north-south glaciated valley(s), the present-day beaches adjacent to the site, and the degraded beach barrier with backing *Phragmites* reedswamp at Tralispean beach (land use delineated in ArcGIS from optical satellite imagery).

postglacial sediments. Now they contain an extensive area of grass-sedge wetlands, with a *Phragmites* dominated reedswamp. This has formed behind a low-elevation blocking beach-barrier composed of sands and cobbles, to the seaward of which lies Tralispean Beach. The valley to the west enters into Tranabo Cove, which is backed by rock cliffs and coarse clastic beach sediments.

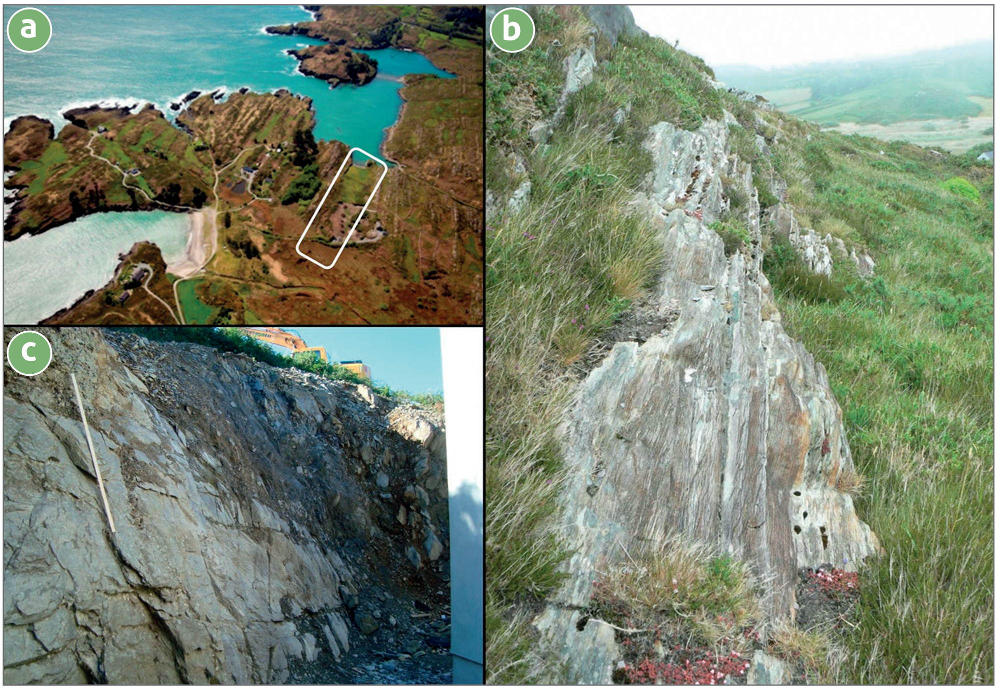

Figure 2a: The site area (white box), showing Tralispean beach (nearest camera) and Tranabo Cove, looking west to the entrance to Lough Hyne. The area's approximate east-west aligned folded sandstones, quartzite and slate rock structures can be clearly seen.

Figure 2b: Exposure of bedrock at the site, showing the steep angle of dip and southwest-northeast direction of strike.

Figure 2c: Exposed basal rock section in the West Cork Sandstone Series at the site, showing common structures in the folded slates and quartzites.

The sediments of interest lie within a rock-structured trough that divides the cliffed headland of Drishane Point from the higher elevated land to the north. This headland is composed of resistant sandstone and quartzites, rising to heights of >30m ODM (Figure 3); the surface is characterised by rock-controlled drainage lines, with outcrops of bedrock. A vegetation cover, dominated by grasses, sedges, heather and bracken, lies above glacigenic sediments, peat and mineral soils that are trapped within rock hollows (Figure 2). The trough is aligned along the rock strike in a southwest to northeast direction and rises from sea level to a saddle-shaped col at about +18.5m.

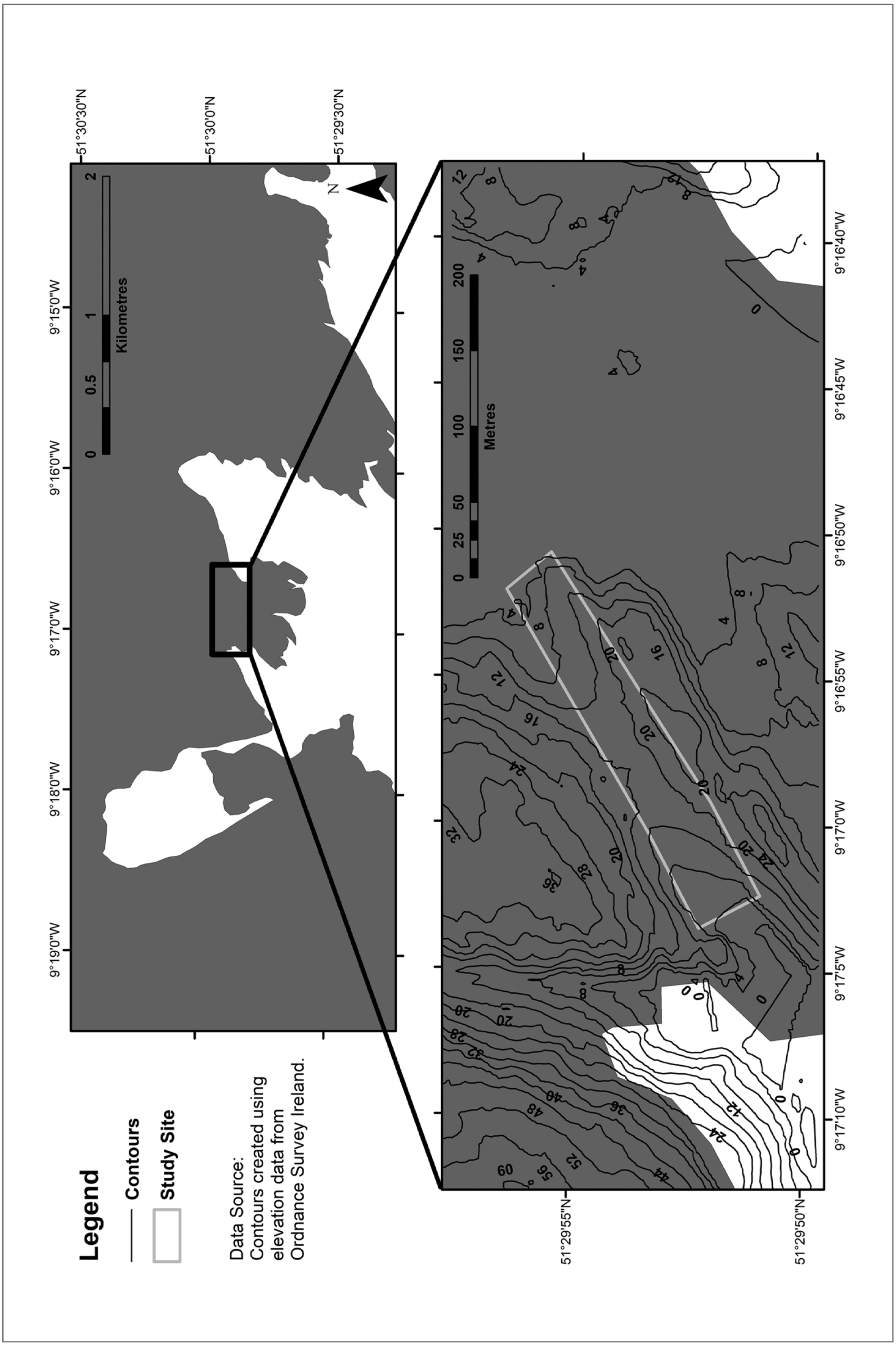

Figure 3: Elevation map of the site and surrounding area.

On the western side of this saddle-shaped area, the lands have been divided historically into a series of enclosed fields, now disused. Some earlier ground excavations and small-scale agriculture in the area provide exposures of the sedimentary sequences and bedrock (Figure 4). To the east, the lands are being used for agriculture by the present owner and it was through this work that the sedimentary sequence was discovered. Either side of the saddle area are extensive exposures of rock, developed as steep slopes and a dissected upland terrain. These form the bounding southern and northern slopes to the site, supporting rough grassland, gorse and patches of briars (*Rubus fruticosis* Agg.).

Figure 4: Section in the shelly fine- to medium-sized sands above, and underlying glacigenic sediments (a clast-rich, fines-supported till/ geliflucted diamicton) below. The boundary between these is sharp, but with evidence of some reworking of the top 0.05-0.10m of the glacigenics, as shown from admixture of the overlying sands into the glacigenics and the presence of rip-up structures at the contact with the sands.

Investigations in neighbouring coastal areas

Reconnaissance investigations of coastal sites between Lough Hyne and Kinsale began in 2017. These have focussed on examining similar high-elevation areas, in order to better understand the regional significance of the Tralispean Sands Unit and associated geomorphological features. Areas of particular interest have been those cited in maps, historical records, field studies and in folklore as recording coastal impacts of the Lisbon 1755 tsunami (e.g., Hickey, 2015; Farrell *et al.*, 2015; Beese, 2015, 2017; Devoy, 2000). Whilst this fieldwork is in its early stages, a potentially significant exposure of elevated sand-dominated sediments has already been discovered at Harbour View (Coolmain Bay), close to Courtmacsherry. A thick (> c.2.5m) and massive sediments Unit, composed of fine-medium sized sands, has been identified at this location. The sands are developed from a sharp basal sedimentary contact with underlying bedrock and glacigenics (till) surfaces, as at Tralispean. These sediments extend from c. 4m ODM at the shoreline, inland and northwards to levels > c. 11m ODM. Visible remains of shells (whole or, broken) were absent in the sedimentary exposures studied. Microscope examination of sediment samples taken from these exposures show the presence of a significant shell carbonate fraction (particle sizes < 0.5mm) in the sands. The sediments continue westwards for c. 500m, variably thinning and increasing in height, along the low coastal cliffs on the western side of the bay (ITM grid 552994, 544069). An informal interview was conducted with a landowner where the sands are exposed, to establish whether any local knowledge existed of the sands and their origin. The landowner and his family are long established residents of the area. It was clear from the interview, together with map and other archival documents, that there is a good knowledge of historical land use changes at the site, from at least the 18th Century. Discussion indicated it is likely that the sands were emplaced by the tsunami run-up of the 1755 Lisbon event (Niall Hegarty, 2017, *pers. comm.*).

Methods

Initial mapping of the Tralispean site was undertaken using a high-resolution differential global positioning system (Trimble ProXH dGPS). This established the aerial extent and altitude of the study area. Survey points were spaced 5m apart along the boundaries of the former fields, with further internal transect lines placed 15m apart and perpendicular to these boundaries, with readings again taken at 5m intervals (Figure 5). The dGPS data were subsequently processed and interpolated using ArcGIS software (version 10.2); this was validated against LiDAR data obtained from the Ordnance Survey of Ireland.

The stratigraphy and sedimentary characteristics of the Sands Unit were investigated by coring, and through open-excavation sections cut into the sediments (Figure 4). A total of 17 primary, georeferenced boreholes were sunk, extending through the sediments as far as the underlying bedrock or consolidated glacigenics (Figure 5). A number of additional, reconnaissance boreholes were also made across the study area, to help establish the up-slope limits of the sands on either side of the topographic saddle. The main boreholes were spaced c. 15m apart along a southwest to northeast transect across the site (Figure 5), and their locations were recorded using dGPS (Hussain, *et al.,* 2006; Lange and Moon, 2007). Sediments from boreholes 1 to 16 were collected using Eijkelkamp-pattern combination clay/sand and sands auger heads, with the sedimentary characteristics recorded in the field using the Troels-Smith scheme (Troels-Smith, 1955; Dawson, 1999).

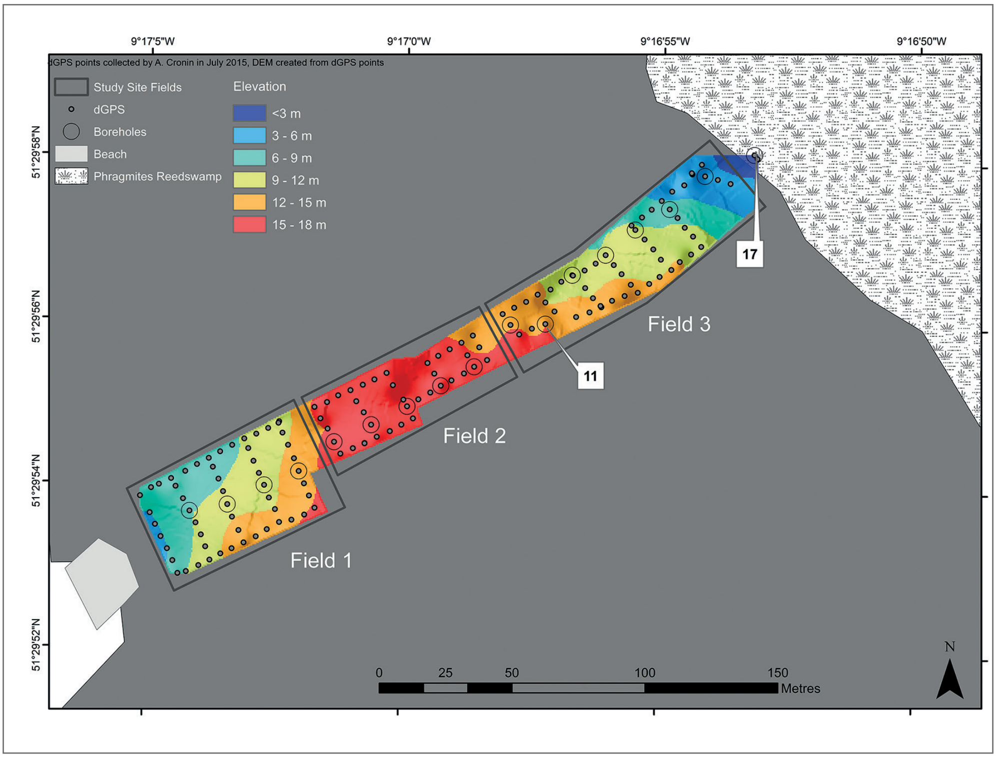

Figure 5: The study site, showing the three historically divided enclosed fields, now disused, which are numbered from west to east here as Fields 1-3 (the present area of cultivation is situated within Field 3); the main dGPS points and transect grid; the borehole locations (boreholes 11 and 17 highlighted); ground heights above ODM; and the reedswamp.

Based on the site stratigraphic work, Borehole 11 was selected for detailed examination, since it provided the greatest depth of sediment (c. 1.4m), contained visible sedimentary structures, and offered the best representative profile for the Sands Unit.

Borehole 17 was taken at the edge of the reedswamp to the east of the site and penetrated a grass-sedge peat (thickness c. 2.3m) that had formed above the Sands Unit. Additional cores have been taken subsequently at this location, to further examine the spatial and chronological relationships between the Sands Unit and the swamp. A gouge-pattern corer (1m long x 0.05m wide) was used to investigate these organic-dominated sediments and for sediment sampling. Samples of the peat overlying the Sands Unit at this location were sent for AMS radiocarbon dating (Beta Analytic Inc., USA, 2015), in order to obtain an indicative minimum age for deposition of the sands. This sampling followed established guidelines for taking samples in the field and later laboratory preparation for radiocarbon dating and other analyses (Devoy, 1979, 1982, 1987; van de Plassche, 1986). Care was taken to remove any modern, diachronous plant rhizomes, particularly of sedges and grasses, including those of *Phragmites*.

Sediment samples from boreholes 11 and 17 were examined; these included particle size analyses, loss-on-ignition (LOI%), carbonates content and micro-fossil studies as detailed below. Particle size analyses were based on the percentages of Total Sediments (Σ) of carbonates and non carbonates, and were undertaken using sieving techniques for the coarse particle sizes c. <1m – 16mm (0-14 Φ), with the dominant fine sediment fraction examined using Malvern Mastersizer laser scanning techniques (Malvern Mastersizer 2000 User Manual, 2007). LOI% for total free organic carbon content used a combustion method, with heating in a muffle furnace at 550˚C for 4 hours (Chagué-Goff *et al.,* 2002; Font *et al.,* 2013; Heiri *et al.,* 2001). For the shell and constituent carbonates fraction of the sediments, samples were heated at 950˚C for 8 hours (Font *et al.,* 2013). Any shells or shell fragments found in the samples were first identified and recorded, before being returned to the sample for heating. Shells were also identified from open field sections and the core materials.

Samples of sediments were taken from the exposed sand sections in the field (e.g., bulk samples of c. 0.5kg) and from the boreholes. These were prepared in the laboratory for foraminifera, ostracoda, pollen and diatom examinations. Identification of the micro- and macro-fossil flora and fauna assemblages found were made using standard taxonomic texts (e.g., Moore and Webb, 1978 for pollen and spores; van der Werff and Huls, 1958-1974; Spalding *et al.*, 2000 for diatoms). Marine and brackish-water mollusca identification was based on McMillan (1968), though separation of terrestrial species was not attempted. It was discovered rapidly in this work that very few diatoms were present in these sediment samples. Further, given the absence of diatoms, it was also judged unlikely that foraminifera and ostracoda would be present in the sands (Hussain, 2010) and, consequently, further investigations for these microfossils was discontinued in this initial study. Pollen and spores in the organic sediments (peat) above the sands in borehole 17 were also found to be sparse, consisting mainly of grass and sedge pollen. Some tree, shrub and herb taxa were also identified, these included the pollen of *Pinus, Salix, Betula, Corylus type, Filipendula* and *Roscaceae*. Pollens of the sedge *Cladium mariscus* were also identified. This palynological record provides no definitive information at this stage for use as a relative dating technique. Pollen and spores are too sparse, as might be expected from a reedswamp environment, and the taxa present are all representative of local plant assemblages.

The sub-surface characteristics of the sediments were investigated using ground-penetrating radar (GPR). The aim of this survey was to reveal any potentially significant sedimentary horizons and other structural features within or underlying the sands, such as, indications of back-wash deposits, non-planar erosion surfaces, abrasion scours and the occurrence of boulders within the sands (e.g. Reineck and Singh, 1975; Switzer *et al.*, 2006; Switzer and Jones, 2008; Koster *et al.,* 2011, 2013, 2014; Goff *et al.,* 2012). Subsequent work, which is still ongoing, has focused on examining the stratigraphy of the reedswamp area behind the beach barrier at Tralispean. An approximately northwest-southeast aligned short core-transect has been established (Figure 5), with the objective of clarifying the spatial, chronological and process-driven relationships between the formation of the Sands Unit and the development of peats and other sediments within the reedswamp.

Results

Figure 6 shows the thickness of the Sands Unit above the basal rock and consolidated glacigenics, with the dGPS data establishing that this unit reaches > c. +18.5m ODM (in the area of Borehole 6, Field 2). The sands in-fill the entire valley-trough area behind Drishane Point.

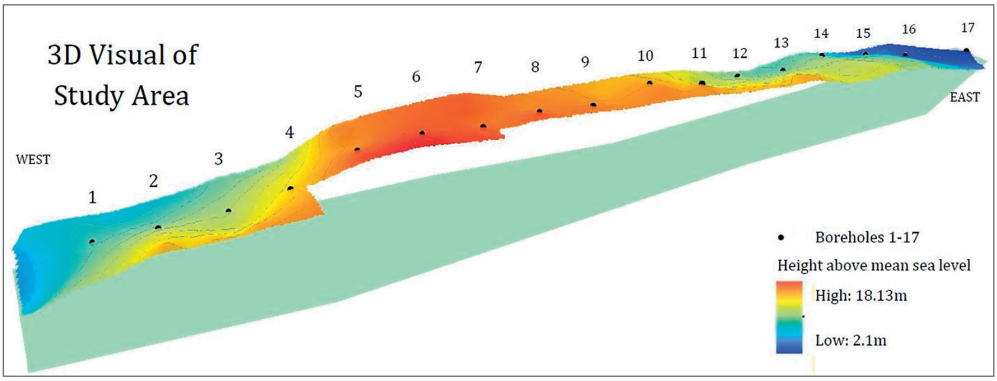

Figure 6a: Terrain model of the Sands Unit showing location of the boreholes.

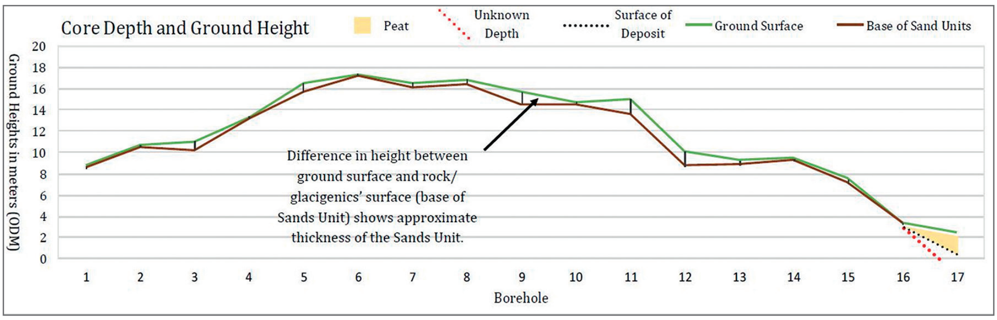

Figure 6b: Cross-section showing interpolated thickness of the sediment above bedrock.

The site is scattered with large to mega-sized boulders at the surface. These range in length from c. 1-4m and are mostly rectangular or trapezoidal in shape, with the longer a- and b- shape axes dominant, producing many flat, raft like megaclasts, some >2m in size (Figure 7). They are all derived entirely from the local West Cork Sandstone rocks.

Many of the boulders in Field 3 had been excavated from the sands by the present landowner, as part of ground clearance operations, and left stacked on the site. In spite of this activity, the GPR records (Figure 8), and some exposed field-sections on the eastern side of the site, confirm the presence of additional boulders *in situ* within the Sands Unit. The GPR study confirmed that the Sands Unit covers the whole of the surveyed area, with the thickest parts occurring in Fields 2 and 3. The GPR also evidenced the occurrence of shallow, interconnected 'basins' containing the sands ranging from c. 0.2 to 2.25m in depth (Figure 8a).

Figure 7a: A rectangular, raft-shaped boulder excavated from the Sands Unit, lying close to the point of origin; the shelly sands here are under cultivation.

Figure 7b: A smaller boulder (a-axis c. 0.35m) in situ within the Sands Unit.

Figure 7c: Boulders found within the sediments, now removed and stacked at the edge of the excavations.

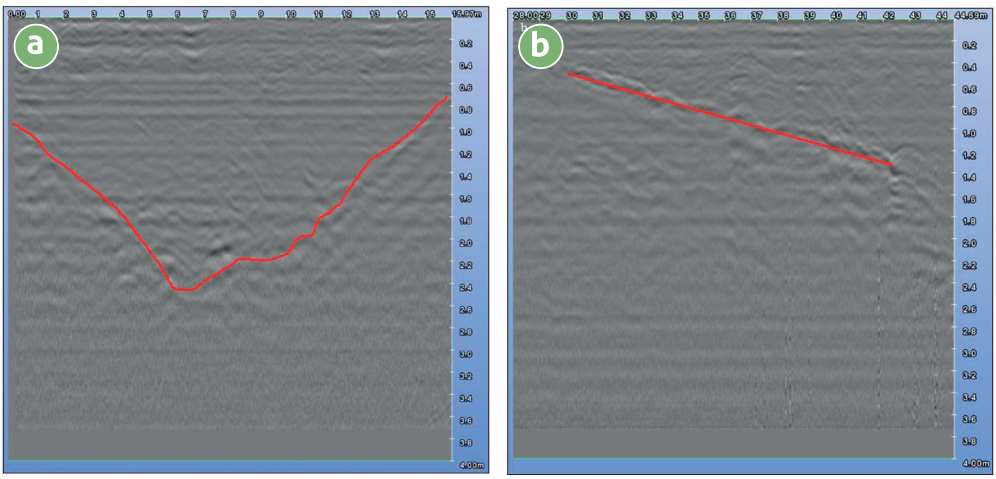

Figure 8a: GPR profile showing a large 'pocket-like' structure within the Sands Unit.

Figure 8b: GPR profile, showing indications of some horizontal bedding of the shelly sands with the surface of a large flat boulder at an approximate angle of c. 40˚within the Sands Unit. Both profiles taken from the west-east transect on the east of Field 2 and into Field 3.

1. From 0.0 (Ground Surface) – c.1.19m, the sediments mainly comprise particles <1mm (0 ϕ), c. 95% total sediments (Figure 9), with 44-49% of medium sand (1-2 ϕ). These core levels have <18% silts and clay sized particles (4-10 ϕ), with only small differences in coarse sand values 0.6-2mm (>0.5 ϕ), varying from 12-28% between the top and base of the sample core.
2. At the base, from c. 1.20-1.40m, coarser particle sizes occur (c. 50% of the sediments > 1mm), with c. 10% of the sediments as silts and clay. The boundary with the

underlying bedrock and surface of the glacigenics was found often to be sharp (Figure 3) and is placed at c. 1.32m below ground surface in Borehole 11; the coarsening of the sediments at these levels is probably accounted for by the occurrence of glacigenic deposits immediately above the bedrock.

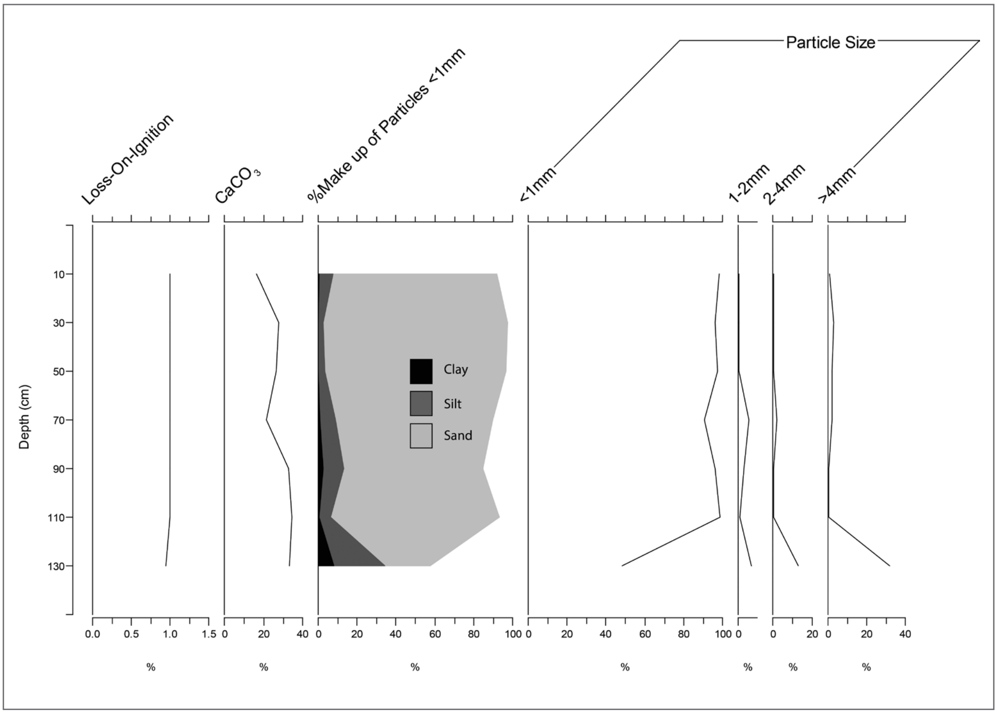

Figure 9: Sediment investigation results for borehole 11, including Loss-On-Ignition, Particle Sizing and Carbonate Content tests.

Overall, the particle size data indicate that the Sands Unit consists of relatively homogenous fine to medium sands, as supported by visual field observations of the sediments in sections on-site.

The LOI% data record uniformly low amounts of organic material incorporated in the sands, c. 1% total sediments and of <1% values below c. 1.15m in the basal glacigenics (Figure 9). In contrast, high frequencies of carbonates are found from 0.8-1.3m, having values of >30% total sediments and falling variably to c. 20% above 0.8m. The carbonates appear to come mainly from shell material, with examination of sands from Borehole 11 and from field observations on-site showing the occurrence of many shells and shell fragments within the sediments. These are dominated by juvenile forms of marine species, specifically *Patella vulgata*, *Patella* spp. (Limpets); *Littorina littorea* and other *Littorina* spp. (Periwinkles), *Turitella communis* (Common Tower Shell), and other Spire shells, all of which are indicative of rocky, open coasts and sub-littoral marine conditions. Some of the shells found are preserved whole, or as large fragments, but comminuted shells predominate. Individuals and fragments of *Hydrobia ulvae* Lavier (Spire Shell) were also found: these are representative of estuary and saltmarsh settings. Most of the intact shells and larger fragments appear to occur in the lower levels of the unit, with the highly broken and the juvenile shell material abundant throughout the sequence. This may represent some size and/or shape separation of these carbonates upwards through the sediments. Many fresh shells of a few species of land snails, such as commonly occur on dune vegetation, were also found within the top sand levels.

At its eastern end, the Sands Unit extends into and is overlain by a fibrous grass-sedge dominated peat deposit that has formed behind the coastal barrier. The poorly humified, loose and unconsolidated nature of this peat indicates that it is likely of relatively recent origin. A sample was taken from the base of this deposit, where it lies directly above and in contact with the Sands Unit. This has been dated by high-precision AMS radiocarbon methods (Table 1).

Table 1: Details of the AMS radiocarbon assay from the top of the sand unit at 0.0m +/- 0.03 ODM (Calibrated Result – 95% probability).

Tralispean, Cork	Lab. Sample Number	Sample Depth ODM	Conventional Radiocarbon Age (1σ) Years AD	Calibrated Radiocarbon Age, 2σ (Cal BP, Older)	Calibrated Radiocarbon Age, 2σ (Cal BP, Younger)	Calibrated Radiocarbon Age (2σ) Years AD
Depth: -2.30 to -2.40m ODM +/- 0.02m	Beta-415949	c. 0.0m	1560 AD (390 +/- 30 BP)	510 to 430	375 to 320	1465 AD (Cal BP 485)

In more recent work a core transect has been commenced across the reedswamp, starting from Borehole 17, where the Sands Unit lies in contact with the swamp deposits, in a southeast direction towards the present beach barrier at Tralispean Bay. Provisional results obtained from this coring show that a deeper and more complex sedimentary sequence lies beneath the Sands Unit in this area than that observed previously.

Discussion

Field and laboratory analyses confirm the *in situ* occurrence of a sequence of marine sands (the Sands Unit) at Tralispean Bay, West Cork, reaching from heights of c. -2m to > +18m ODM. This is above the known heights of offshore waves (Figure 10) and storm surges around Ireland's coasts today (Devoy *et al.,* 2004, 2015; Gallagher *et al.,* 2013, 2014; pers. comm. Kinsale Energy Ltd., *pers. comm.*, 2017. See also Gallagher *et al.,* 2013, 2014, for more recent wave and associated data for Ireland). Local observations suggest that storm surges reach maximal levels of between +10m to +12m ODM within the outer rock-cliffs areas of Tralispean Bay (Henderson, *pers. comm.*, 2017). Key questions arising from this work include the need to:

1. establish the age of the Tralispean Sands Unit,

2. identify with greater certainty the nature of the event, or events, and hydrodynamic process that led to deposition of the sediments, and
3. establish the connections, if any, with similar sedimentary sequences now identified on adjacent coasts.

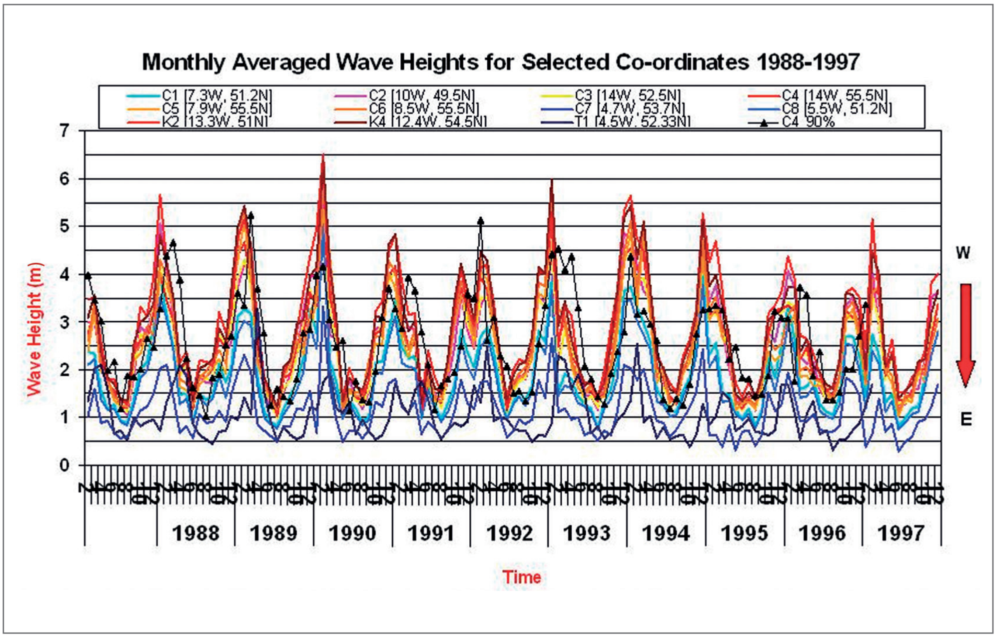

Figure 10: Distribution of mean monthly wave heights for Ireland's offshore coastal waters. These are modelled hindcast wave conditions for the period 1988-1997. The data are validated with wind-wave buoy observations from regional locations (Devoy *et al.,* 2004). The figure's colour-coded key gives the Latitude and Longitude positions of these observation points: C4-C6 = northern coasts, C3, K4 and K2 = western, C1, C2, C8 = southern, C7 and T1 = eastern. The central south coast data, covering the Tralispean Bay area, show intermediate mean wave height values of 3-4m. Offshore wave heights in individual storms reach levels of 7-10m on these southern coasts.

Dating the Tralispean Sands Unit

Local remembrance and folklore suggest a possible 1755 event origin for the sediments. As at Harbour View, short telephone-based interviews with local landowners and residents of the site area showed that there is a good knowledge, passed down through families, of the historical and land use changes that have taken place here since at least the early 19th Century.

Information on a more precise dating of the Sands Unit remains equivocal. A future robust radiometric dating programme of the Sands Unit, and more complete understanding of its palaeoenvironmental setting, are both critical to determining the origin and processes that led to the deposition of the marine sands (Devoy *et al.*, 2015).

The AMS radiocarbon date obtained from the base of the peat in the reedswamp, at the eastern end of the site (Figure 1), suggests that this biogenic sediment began forming c. 485 years before present (BP) (i.e., c. 1465 AD). The peat cores extracted during the sampling operations, both in the field and laboratory, showed no indication of material in-washing, remobilisation or reworking of the organic material overlying the Sands Unit. The physical-chemical characteristics of the biogenic sediments, together with the very sheltered depositional environment of the reedswamp, supports this view. Since the Sand Unit underlies the peat, then both the sands and the event that led to its deposition must be at least as old as this basal date for the peat. The structure, texture and composition of this peat in the reedswamp at Tralispean is similar to many biogenic sequences found forming in analogous beach-barrier protected coastal wetland locations on Ireland's south and west coasts today (e.g., Carter *et al.,* 1989; Devoy *et al.,* 1996; Delaney *et al.,* 2012). These coastal sites typically show stratigraphies consisting of a surface of basal bedrock, or glacigenics, above which are found thin clast-rich organics levels, which are initially replaced upwards by a wood peat (dominated variably by oak, alder, willow and pine) and then by a grass-sedge peat; these sequences commonly give ages of 2,000-5,000 BP. This sedimentary sequence may be interleaved by levels of thin silt-clays and/or sands, depending on the physical configuration and exposure of the coastal site to both river and marine flooding. These stratigraphies are found now most commonly in exposed coastal settings.

The biogenic sequences at Tralispean are protected by the beach barrier, and whilst preserving older material, continue the development of organic accumulation into the present day. The exploratory boreholes (17-19) developed where the Sands Unit is found at the margin of the reedswamp show that the lower part of the biogenic sediments have characteristics similar to those found at other coastal sites, but are overlain by more recent materials. The upper levels (c. 1m of biogenic-rich sediments) have a loose fabric, are relatively un-humified, and generally show the compositional characteristics of recent formation (*viz.* Troels-Smith, 1955); all of which concurs with the AMS ^{14}C dating. However, depending on the time significance of the underlying hiatus with the upper surface of the Sands Unit below this peat, then these sands may have been deposited well before the age indicated by the radiocarbon assay on the base of the peat.

Overall, the evidence obtained to date indicates that the organics sample is of recent age (Smart and Frances, 1991; Dickin, 2008) and the peat above the marine sands began growing within the last c. 1,000 years. This interpretation is supported by the biostratigraphy, which shows the accumulation of c. 1.0m of relatively loose and un-humified peat beneath the present reedswamp vegetation. The apparent recent age for the peat may be due to human impacts at the site, with past turf cutting removing older peats and biogenics, as has occurred at Dunworley Bay, near Courtmacsherry at Ballycotton Bay further east and at many other coastal locations in Ireland. These latter sites typically show periods of peat removal from the early 1800s onward (e.g., Carter *et al.,* 1989; Devoy, 1983). However, the date obtained at Tralispean would place the peat development before the common practice of coastal peat cutting became established, in or after the late 18th Century (Feehan and O'Donovan, 1996). Clearly, more radiocarbon and other radiometric-type dates, e.g., Optically Stimulated Luminescence (OSL) or Electron Spin Resonance (ESR) techniques (e.g., Lowe and Walker, 1997; Huntley and Clague, 1996), are needed to help validate the age of the sands, and obtaining these is planned as part of future research at the site.

Possible process origins of the Sands Unit

As well as establishing the age of the Sands Unit, it is also necessary to consider what other processes (such as geomorphological) were responsible for its deposition. A review of the relevant literature relating to similar sedimentary sequences found elsewhere identifies six possible mechanisms (in no particular order):

Human intervention

Agricultural practices to improve the often-poor soil conditions in these environments, by carrying sands, shell and seaweeds from beach and wider intertidal areas to adjacent fields and higher grounds, has commonly undertaken by coastal communities in Ireland and elsewhere since at least the 19th Century (e.g., Gilbertson *et al.,* 1999; Ritchie and Angus, 2012). In the Tralispean area, evidence of post-18th Century settlements, with the remains of abandoned stone cabins, field walls and linking trackways to the coast for farming and fishing activities, are still evident.

Such human activity, however, can be discounted as the origin of the Sands Unit at Tralispean. This is primarily because of the large quantity and areal extent of the sediments recorded (with > c. 14, 000m^3 of sands deposited over the area); as well as, the lack of evidence for any mixing of the sands with plants or other organic materials to create a soil and the undisturbed, massive and sorted character of the Sands Unit. Informal interviews with landowners, and the folklore of the area regarding past land uses at the site, support this interpretation of the physical evidence. Whilst field conditioning was practised, local knowledge of the existence of the sands meant that people were more interested in finding ways to exploit and mine the sand deposit for use elsewhere. These interviews established that some 8,000m^3 of the sands were eventually excavated from the site in the 1980s, leaving the open sediment sections found at the western side of the site (Figure 4), with the sands being shipped out of the area by sea from Tranabo Cove (e.g., McCarthy, *pers. comm.*, 2016).

Glacial transport and deposition

Given the significant impact of glaciation on this area (e.g., Warren, 1979, 1980, 1981; McCarron and Coxon, 2009; Coxon *et al.,* 2017), and the existence of two ice meltwater escape valleys bounding the site (Figure 1), possible ice-linked causes for the sedimentary sequence must be considered. However, the characteristics of the Sands Unit do not fit with those reported for glacigenic deposits from other locations in Ireland, which are most commonly described as comprising consolidated to semi-consolidated, heterogeneous and non-sorted diamictons (e.g., Drewry, 1986; McCabe, 1987; Ehlers *et al.,* 1991; Siegert, 2001; Knight *et al.,* 2004; Coxon *et al.,* 2017). Such sediments also occur throughout the Tralispean site area, but they are distinct from the sands, and form the over-consolidated basement deposits underlying the marine sands themselves (Figures 2 and 4). An ice-melt, glacifluvial source for the Sands Unit is equally unlikely, given the fining upwards sorting, the high carbonates and marine shell content of the sands, and the lack of any diagnostic internal structures, such as sedimentary 'cyclicity', cross-bedding, ripple forms or linked structures that would usually be associated with such deposits (McCarron and Coxon, 2009; Coxon *et al.,* 2017). The inclusion of the megaclasts described previously, within the dominant fine-medium sand matrix, also poses significant process problems for deposition of the shelly sands by glacifluvial mechanisms, though mechanisms producing equifinality are possible (Hart, 1986; Beven and Freer, 2001). Further, the sediments at the Tralispean site lack a clear morphological and spatial connection to high-energy coarse, sorted clastic glacifluvial sediments found elsewhere in the area (Lewis, 1977; Warren, 1980; Harrison and Mighall, 2002). Instead, their homogenous but highly-sorted nature, together with the included marine shell fraction and the particle size patterns (Figure 8), would further support the idea of a marine water mechanism for their deposition.

Beach development from interglacial- or interstadial-age coastal processes

Because of the sedimentary hiatus between the Sands Unit and the overlying young peat, there remains a possibility that these marine sands are the upper levels of a beach formed by wave and storm action during a period of high relative sea level in an earlier interglacial. However, this explanation is considered unlikely given knowledge of the Late-Quaternary raised beach sedimentary sequences in the region (e.g., Devoy, 1983; McCabe and O'Coffaigh, 1996). The Sands Unit is shown to overlie glacigenic sediments in many locations at the site, and it can be followed landwards to heights of >18m ODM, a depositional height range that is both well below and also above the levels of any of the now long-established 'raised beach' type sediments in the south of Ireland (Synge, 1985; Devoy, 1983, 2005; Coxon *et al.,* 2017). The nearest known raised beaches are at Courtmacsherry, West Cork, where they form part of the long-studied Late-Quaternary lithostratigraphy of the south and west coasts of Ireland, as linked to that of south and western Britain (e.g., Wright and Muff, 1904; Bowen *et al.,* 1985; Jones and Keen, 1996). These raised beaches are composed of well-sorted, interbedded and ferricreted sands and

Figure 11: Raised Beaches above the rock-cut South of Ireland Platform in Courtmacsherry Bay

gravels, dominated by coarse clastics of fine-medium gravels sizes (Figure 11); they are positioned variably above glacigenic diamictons, but most occur commonly above the much earlier South of Ireland shore platform (e.g., Devoy, 1983, 2005, 2009).

The base of these raised beaches, identified in Courtmacsherry Bay and more widely along Ireland's southern coasts, has only ever been found at heights above c. 6.0m ODM, whereas the Sands Unit at Tralispean extends downward to below present sea-level. Furthermore, sediments formerly interpreted as raised beaches occur regionally below c. 8.0m ODM and do not contain marine shells although they may once have done so, with the shells having since been removed by water leaching over time (e.g., Bowen *et al.,* 1985). The raised beach sequences found on Ireland's south coast have been reinterpreted as more probably tidewater glacifluvial sediments that date from the last stages of ice retreat from Ireland's present offshore zone, which itself formed post c. 24k years ago (McCabe and O'Coffaigh, 1996; Knight *et al.,* 2004; Coxon *et al.,* 2017). Whatever the hydrodynamic process origin for these raised beaches might be, their sedimentary characteristics are very different in appearance and composition to the Sands Unit found at Tralispean. Further, the lack of visible sedimentary structures (e.g., cusps and ripples) and planar layering within the marine sands is atypical of regular forms of wave-induced beach sediment deposition and hydrodynamics (e.g., Reineck and

Singh, 1975; Masselink *et al.*, 2011; Dronkers, 2005; Hardisty, 1990, 1994 ; Scott *et al.*, 2011; Randazzo *et al.*, 2015).

Impact of an extreme 'rogue' wave

In this context, O'Brien *et al.* (2013) drew attention to the possibility of the occurrence of freak and 'rogue' waves in the North Atlantic potentially impacting these coasts. Freak waves that are predictable components of open-ocean long period swell waves can often intersect the coast at heights of 5-8m ODM. Less common is the development of randomly occurring, non-linear hydrodynamic rogue waves. In open-water North Atlantic settings off Ireland's coasts, such waves can reach heights of double the sea state significant wave height, at maximum observed values of c. 20-24m above still water levels. However, it is unlikely that such waves could affect onshore areas of coast to such heights, and even those that occur in open water are mostly well below the height of the Tralispean Sands Unit.

A large storm surge event, or a series of storms

Of the remaining possibilities for the deposition of the Sands Unit, the result of storm surge or tsunami action seems most likely (e.g., Scheffers *et al.*, 2010; Williams, 2010). However, past and contemporary observations in the study area, together with modelled outputs of past and future wave and storm surges for the south coast of Ireland (e.g., Devoy *et al.,* 2004; Wang *et al.,* 2008; Gallagher *et al.,* 2013, 2014, 2016; Gleeson *et al.,* 2013) (Figure 9), indicate that storm action only reaches maximum heights of <10-12m ODM. Given knowledge of former sea level positions and coastal development in the region, there is no evidence that surge levels have been higher in the last c. 2000 years (e.g., Duffy *et al.,* 1999; Devoy *et al.,* 2006; Delaney *et al.,* 2012). Since the Sands Unit at Tralispean is developed predominantly at elevations above c. 10m ODM, and extends to heights of c. +18.5m ODM, this alone suggests that a storm event, or even a temporally linked series of storms, is unlikely to explain emplacement of the Sands Unit. It is recognised, however, that most coastal wave and storm deposits lack unique and conclusive sedimentary indicators of their origin, other than that they result from high-energy hydrodynamic conditions (See Table 2 and Goff *et al.,* 2012).

Impact of a tsunami caused by an earthquake, from a meteorite or asteroid impact, or submarine sediments slides

Until recently, investigation of the sedimentary differences between storm, tsunami and other high-energy event deposits, has been limited, as has sedimentological and paleoenvironmental work aimed at defining the occurrence of these events (e.g., Baptista *et al.*, 1998; Fujiwara *et al.,* 2000; Bondevik *et al.*, 2005; Kortekaas and Dawson, 2007; Goff *et al.,* 2012; Bryant, 2014; Santiago-Fandiño *et al.,* 2016).

Table 2: Distinguishing features and characteristics of tsunami and storm deposits (Kortekaas and Dawson, 2007; Goff *et al.*, 2001). Features present in Tralispean Sands Unit are highlighted in bold.

Evidence	Tsunami	Storm
Morphological	Washover fans occur behind breached barriers.	Washover fans occur behind breached barriers.
Stratigraphical	Stratigraphy and sedimentary units thin inland and become discontinuous Fine inland Erosional basal contact **Have a larger inland extent** **Higher elevation.**	Units thin inland and/or also Fine inland Erosional basal contact Have a relative smaller inland extent.
Sedimentary	**Boulders** One or more fining upward sequence, but sediments can be homogenous **Interclasts from underlying material** **Loading structures at base** **Bidirectional imbrication** **Poorly sorted (particle size ranging from mud to boulders)** **Sedimentary structures are very seldom found.**	**Boulder deposition has been reported** Fining upward sequences, or can be homogenous Interclasts, not found **Loading structures do occur** Unidirectional imbrication Some sorting possible Sedimentary structures more common.
Geochemical	Increases in geochemical elements, indicative of a marine origin	No information found; but some similar signature is expected, due to marine origin of the sediments
Palaeontological	Marine fossils: possible presence of ostracoda, foraminifera and diatoms Increased diversity (mixture marine and brackish fossils) **Fossil remains range from relatively well to poorly preserved** Plant debris/ fragments **Broken and whole shells, or shell-rich units** **Rafting light materials (common)** Buried plants at base.	Marine fossils: absence of ostracoda, presence of diatoms and foraminifera Mixture of marine and fresh water fossils Fossils poorly preserved Plant debris/ fragments **Broken shell fragments** **Rafting of light materials can happen** Buried plants at base.
Summary of the key characteristics of tsunami event deposits	These include basal erosional surfaces in sediments, anomalous coarse sand layers, imbricated boulders, chaotic sedimentary bedding, together with the occurrence of rip-up mud clasts, normal and inverse particle size grading, a landward-fining trend for sediments, horizontal planar laminae, cross-stratification, hummocky cross-stratification, massive sands, sediments rich in marine fossils, sands with high Potassium, Magnesium and Sodium elemental concentrations and sand injections (Shanmugam, 2012).	

These are significant gaps in existing coastal geomorphological research. Table 2 provides a summary of the key sedimentary and other environmental features that may be used to identify and differentiate between deposits from tsunami and from storms respectively. Based on these characteristics, the following may be recognised as the best identifiers of tsunami sediments:

- Poorly sorted sediments
- Particle sizes ranging from mud to boulders
- Deposits found at unusually high elevations
- The presence of loading structures at the base of the deposit
- Presence of large boulders and clasts, which have been rafted ashore
- A large inland extent of marine sediments
- Occurrence of relatively well-preserved fossils, as well as broken remains, and commonly with the inclusion of juvenile forms of organisms
- The presence of ostracods, foraminifers and marine diatoms.

Many of the sedimentary structures and forms found in different tsunami deposits are common in character. However, most of the associated depositional features indicate only the high-energy nature, or the marine origin of the sediments (Albon *et al.,* 1991; Dawson and Shi, 2000; Gelfenbaum and Jaffe, 2003; Jaffe *et al.*, 2003; Engel and Bruckner, 2011). Storm deposits often show similar characteristics to those of tsunami and distinguishing storm from tsunami deposits is difficult (Kortekaas and Dawson, 2007; Devoy *et al.,* 1996; Farrell *et al.,* 2015; Bryant, 2014; Goff *et al.,* 2012; Haslett and Bryant, 2008). Evidence of tsunami-originating sediments may be split into three timeframes: data from modern events; those from history; and, those from prehistory (Tappin, 2007; Morton *et al.,* 2007; Goff *et al.,* 2012). Of these, observed data from modern-day events enable a direct link to be established between a tsunami event and its resulting deposits. To date, no contemporary observations of any tsunami impacts have been made in Ireland (Hall *et al.,* 2010).

While historical records of tsunami events impacting the Irish coast in the recent past exist, there are few of them (e.g., O'Brien *et al.,* 2013). The publications and references that exist refer mostly to information for specific sites and locations and are of variable reliability, rather than dealing with generic coastal process issues and wider regional-national evidence of former tsunami in Ireland. For the southwest region of Ireland, any interest in the possible potential impacts of tsunami on these coasts is very recent. Publications and references to this theme focus on the geomorphological impact of the Lisbon 1755 event, based upon the available map, historical and other archival records (Farrell *et al.,* 2015; Rosscarbery and District Historical Society, 2015; Beese, 2015, 2017; Larkin, 2010; O'Brien *et al.,* 2013; Jeffers, 2007; Politics Forum, 2009). Although much remains to be done on this theme, work now shows the significant changes that occurred with this event to the region's soft sedimentary coasts, as recorded at, e.g., Kinsale, Dunworley Bay, Longstrand, Owenahincha and Rosscarbery. Although such records may provide useful supplementary evidence to support interpretation of observed possible tsunami deposits, the use of sedimentary, stratigraphic and linked paleoenvironmental approaches are critical in identifying the existence of these events with greater certainty (e.g., Owen *et al.*, 2013; Georgiopoulou *et al.*, 2013; Wheeler and Devoy, 2002). As established at many locations outside of Ireland which evidence tsunami impacts, (e.g., in Britain, France, Portugal, New Zealand, Australia), use of these sedimentary techniques has also been valuable in establishing the significance of these high-wave energy events for past, present and possible future coastal process functioning (e.g., Goff *et al.,* 2004, 2012; Nichol *et al.,* 2007; Haslett and Bryant, 2007, 2008; Delaney *et al.,* 2012; Devoy, 2015a).

Work by Kortekaas and Dawson (2007), Goff *et al.* (2012), Bryant (2014) and others indicates that sedimentary sequences arising both from storms and from tsunami may either have fining upward grain size, or else can be homogenous in character (Table 2). These authors emphasise that tsunami deposits commonly show enormous variability in their sedimentary characteristics. In some locations, tsunami sediments can be represented by a single homogenous layer of sand, while elsewhere these events are represented by a complex of sedimentary layers containing stratigraphic evidence of sediments reworking and re-deposition (e.g., Jaffe and Gelfenbaum, 2002, 2007; Jaffe *et al.*, 2003). It is also likely that on rocky coasts, where sediment supply is restricted, former tsunami can leave no traces at all. Given such diversity in tsunami sediments, it is clearly challenging and difficult to unambiguously distinguish sediments they may produce from those resulting from storm surge or, in some circumstances, even from longer term changes in sea-level (e.g., Dawson and Shi, 2000; Goff *et al.,* 2012).

Table 2 also highlights that a more consistent feature of tsunami events is that their deposits can generally be traced further inland and to a higher elevation than those of storms (Dawson and Stewart, 2007; Dawson, 1999; Devi *et al.,* 2013; Smith *et al.*, 2007; Bourgeois, 2009; Chagué-Goff *et al.,* 2002; Kortekaas and Dawson, 2007; Goff *et al.,* 2012), though storms are recorded as throwing large boulders onto cliff tops >35m ODM on Ireland's western coasts (Carter 1988; Williams and Hall, 2004; Williams, 2010; Jeffers, 2007; Scheffers *et al*., 2010; O'Brien *et al.,* 2013; Dewey and Ryan, 2017). Due to the magnitude of energy and wave hydrodynamics of tsunamis, the associated wave run-up is able to reach progressively higher elevations onshore before terrain frictional and water volume loss factors lead to the dissipation of the wave (Foster *et al.,* 1991). As noted, the Sands Unit at Tralispean extends to c. +18.5m ODM and approximately 90m inland from the seaward-facing cliff at its western margin. It is improbable that a storm could deposit marine sediments at these elevations and this far inland. Increased terrain friction, as presented by the Drishane Point headland, significantly reduces the inland and upward extent of storm waves and their ability to transport and deposit sediments (Morton *et al.,* 2007; Henderson, 2015, *pers. comm.*)

A further significant characteristic of many tsunami is their capability to deposit boulder to cobble-sized clasts up to several kilometres inland, depending upon the shore gradient, wave amplitude and run-up (e.g., Dawson *et al.*, 1995; Nichol *et al.*, 2003; Menzies, 2003; Bryant, 2014). This has been observed and reported for tsunami deposits from several parts of the world: for example, Dawson and Shi (2000) observed coral boulders derived from adjacent areas of a reef in Indonesia after the Flores tsunami; while Bourrouilh-Le Jan and Talandier (1985) described areas of coral reef in Tuamoto (French Polynesia) where large numbers of boulders up to 750m^3 have been transported across the atoll rim and into a lagoon. The Sands Unit at Tralispean also contains numerous megaclasts, composed of the same rock types as are exposed along the present-day shore and in the many rock outcrops across the study area. Some of these boulders have been excavated and moved by the present landowner and stacked in piles around the eastern side of the site (Henderson, 2015, *pers. comm*.), but many remain *in situ* within the sands and were imaged by GPR (Figure 8). The undisturbed boulders mostly show a predominant west-east alignment, co-incident with the axis of the trough-shaped site that the deposit lies in, and consistent with the route way that any hydrodynamic event affecting the site would have had to follow. The dominant direction of approach of contemporary open-water swell and storm waves impacting these coasts is from the southwest and west (e.g., Orford, 1989; Devoy *et al.,* 2004; Wang *et al.,* 2008; Gallagher *et al.*, 2014), and this is likely to also apply to the propagation of any tsunami from the North Atlantic region into the area, as with the 1755 Lisbon event (National Ocean and Atmosphere Administration, 2017; Jeffers, 2007).

The boulders in the Sands Unit are concentrated at the base of the sediments, though a thin layer of sands underlies many of them. Their shape reflects the semi-regular joints and bedding planes observed in the bedrock (Figure 7) and they probably result from shearing by wave, or possibly former ice erosive action although their surfaces lack any evidence of striae or ice abrasion, making it unlikely that they are primary glacial erratics. However, this is not in itself a conclusive indicator of origin here, given the nature of the geology of this area (Lewis, 1977; Harrison and Mighall, 2002). Some erratics and mass-moved boulders do occur on the slopes surrounding the site, as might be expected in this glaciated environment with ice retreat occurring only c. 14,000-16,000 years ago (Devoy, 2005; Coxon *et al.,* 2017). It is probable that, in any tsunami affecting the area, all available loose surface debris would have been swept up in the progress of the water wave over the terrain, and incorporated into the subsequent deposits. In geomorphological terms, evidence for this course of events is necessarily slim. However, given the stratigraphic association of the boulders within the shelly sands, it is more likely that the majority of them were rafted up from former shore zone and deposited, along with the sands in which they occur, by high-energy wave action. A tsunami would be a likely explanation for this type of deposition (Morton *et al.,* 2007; Tuttle *et al.,* 2004).

Conclusions

This study reports on a newly discovered high-elevation coastal sedimentary sequence at Tralispean, southwest Ireland. The preliminary conclusion reached from the site sedimentary and paleoenvironmental information is that this deposit is not the result of human activity, nor of more frequent agents of coastal changes such as storms, but potentially shows the impact on the coast of a tsunami.

The date of occurrence of this event is problematic, as it is currently based on a single radiocarbon date and more definitive evidence is needed before any firm conclusion regarding date can be reached. The next phase of work at the site will focus on seeking this evidence. Although the supporting litho- and biostratigraphic data are consistent with a recent/ historical age for the event, we are not aware of any historical or sedimentary data to indicate a mid-15th Century tsunami in Ireland. Given the lack of any other supporting historical evidence for tsunami in the region, it is more likely that the event recorded at Tralispean/ the Sands Unit is of the 1755 Lisbon tsunami, for which some documentary records do exist for the southern coasts of Ireland.

Whatever the age of the sands, the fact of their existence is relevant to understanding Ireland's coastal geomorphology, since they clearly indicate the operation of an extreme event in the past, and the potential for similar future events in the future. Further, while historical and anecdotal accounts of past tsunami impacts in Ireland exist, the Tralispean site potentially provides the first investigated physical and sedimentary evidence of such an event in Ireland. Other sites with similar high-level marine sands have now been tentatively identified and will be investigated in follow-up work as part of wider programme of extreme event research in Ireland's coastal zone. Further research is now required, including:

- Thorough exploration and analysis of historical documentary and linked records, in Ireland and wider afield, with particular focus on references to coastal catastrophes and rare events;
- Linking the historical records to greater understanding of large-scale coastal processes, such as driven by storm surges and tsunami;
- Further in-depth investigation of the site at Tralispean, including additional geotechnical surveys, as well as stratigraphic, sedimentary and paleoenvironmental examinations, particularly of the back barrier and valley reedswamp environments;
- Numerical hydrodynamic modelling of the Tralispean area to reconstruct and evaluate alternative scenarios for the passage of a tsunami wave at the site and of the magnitude of the event recorded in the sedimentary data examined;
- The provision of more radiometric dates from the peat profile, from the boundary contacts with the Sands Unit. In addition, other dating techniques need to be applied to the sands themselves e.g., optically stimulated luminescence (OSL) dating. This work is needed to establish a firm age for the sedimentary data and to help validate the conceptual understanding of the environmental changes that took place at the site;

- Searching for, and examination of, other sites on the southwest coast of Ireland that might also contain sedimentary or other evidence for this inferred tsunami event.

It is also important to assess the significance of the sediments at Tralispean for coastal functioning in the wider Northeast Atlantic region, while identifying the source of the tsunami event that impacted Tralispean may potentially yield useful information that could help reduce the scale of damage from future such megascale events. Recognising that the instantaneous reorganising of soft sedimentary coasts that result from tsunami is likely to be rare in Ireland, the similar impacts of megastorms operating under climate warming will be more frequent in future. Identifying the signature of former such high energy events, such as tsunami and megastorms, on Ireland's coasts will be helpful now in developing suitable local-regional level management and coastal protection responses (IPCC, 2014a, 2014b; Devoy, 2015a; Neuman *et al.*, 2015; Sanchez-Arcilla *et al.*, 2016; National Climate Change Advisory Council, 2018; UK Climate Change Committee, 2017; EPA, 2018). Finally, continued development of the methods used to distinguish between storm and tsunami deposits could aid tsunami identification elsewhere, enabling the more accurate mapping of their spatial and temporal occurrence, as well as providing additional help in coastal hazards planning and management.

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