Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Research Programme
- Short Call 2020, Final Report -

Lead Applicant Name	Dr Patrick J. Orr
Host Organisation name	School of Earth Sciences, University College Dublin
Project Title	Assessing the potential of Holocene shellbeds in Galway Bay as paleoenvironmental and palaeoclimate archives
Contract Number	2020-sc-037

This report covers the period 1st December 2020 to project end date 31st August 2022

2. (a) Project information:

Executive summary (lay abstract, approx. 250 words):

Shellbeds are high-density accumulations of complete and/or fragmented remains of marine animals – typically gastropods (snails) and bivalves (clams). Episodic shellbeds in a succession represent perturbation of the "usual" conditions under which the sediments accumulated. Shellbeds vary in terms of such as geometry, thickness, and internal structure, and the state of preservation of the shells (their taphonomy), in response to how they formed. Thus, by retrospectively identifying the processes responsible for their formation, shellbeds offer insight into what the ecological and environmental conditions were at the time of their formation.

Distinctive shellbeds (a few thousand years old) dominated by the gastropod *Turritella* occur in a series of sediment cores recovered from below the seafloor of Galway Bay. We have used detailed sampling and innovative 3D virtual reconstructions of these shellbeds to demonstrate that, on the basis of the high quality of preservation and there being a continuous range of shell sizes present, the shellbeds represent *in situ* accumulations; i.e. represents the original population. Limited data suggest the shellbeds are all the same age; if this model is proven by subsequent studies, these distinctive populations developed simultaneously over most of the Outer Bay (over at least 25 x 5-10km!). Why the shellfish communities would suddenly become dominated by this single species, and how long these populations persisted for is the subject on on-going research. Understanding this is key to answering the question: could a similar ecological shift happen again if these marine ecosystems continue to come under increasing stress from human activities?

Results, scientific/engineering targets reached beyond the state of the art and conclusions

Introduction

Benetti et al. (2017) identified a series of shellbeds of Holocene age in cores from Galway Bay (Figure 1) that are typically 0.1 to 0.5 m thick, occasionally up to 0.9m thick, and composed predominantly of *Turritella communis* (hence the term Galway Bay *Turritella* Layers: GBTLs). One shellbed occurs in each core (Figure 2), on which basis the simplest option is that there is one shellbed that is the same age throughout the area, a biological response to some form of environmental perturbation at either a local or wider scale. That interpretation would be consistent with how other Holocene in age, *Turritella*-rich, shellbeds that appear similar in general structure to the GBTLs have been interpreted: offshore western Europe; (Bay of Biscay, France (Naughton et al. 2007), NW Scotland (Baltzer et al. 2015), and the NW Mediterranean (Bassetti et

al. 2016)). There are alternative spatial and temporal models for these communities that would result in one shellbed per core (Figure 2); note the importance of identifying what age each shellbed is to distinguish between these. Shellbeds are common, and can be areally widespread, at certain intervals of cyclical change in relative sea level: for example as transgressive lags. In Ireland, the Holocene saw marked changes over time in relative sea level in response to the interplay of isostatic adjustment, and transgression in response to post-glacial eustatic sea level rise.

Clearly any interpretation of the potential environmental significance of the GBTLs depends on reconstructing first how they formed. ***The project's objective was therefore to test the following***

developed in response to one or more episodes of short-term environmental change.

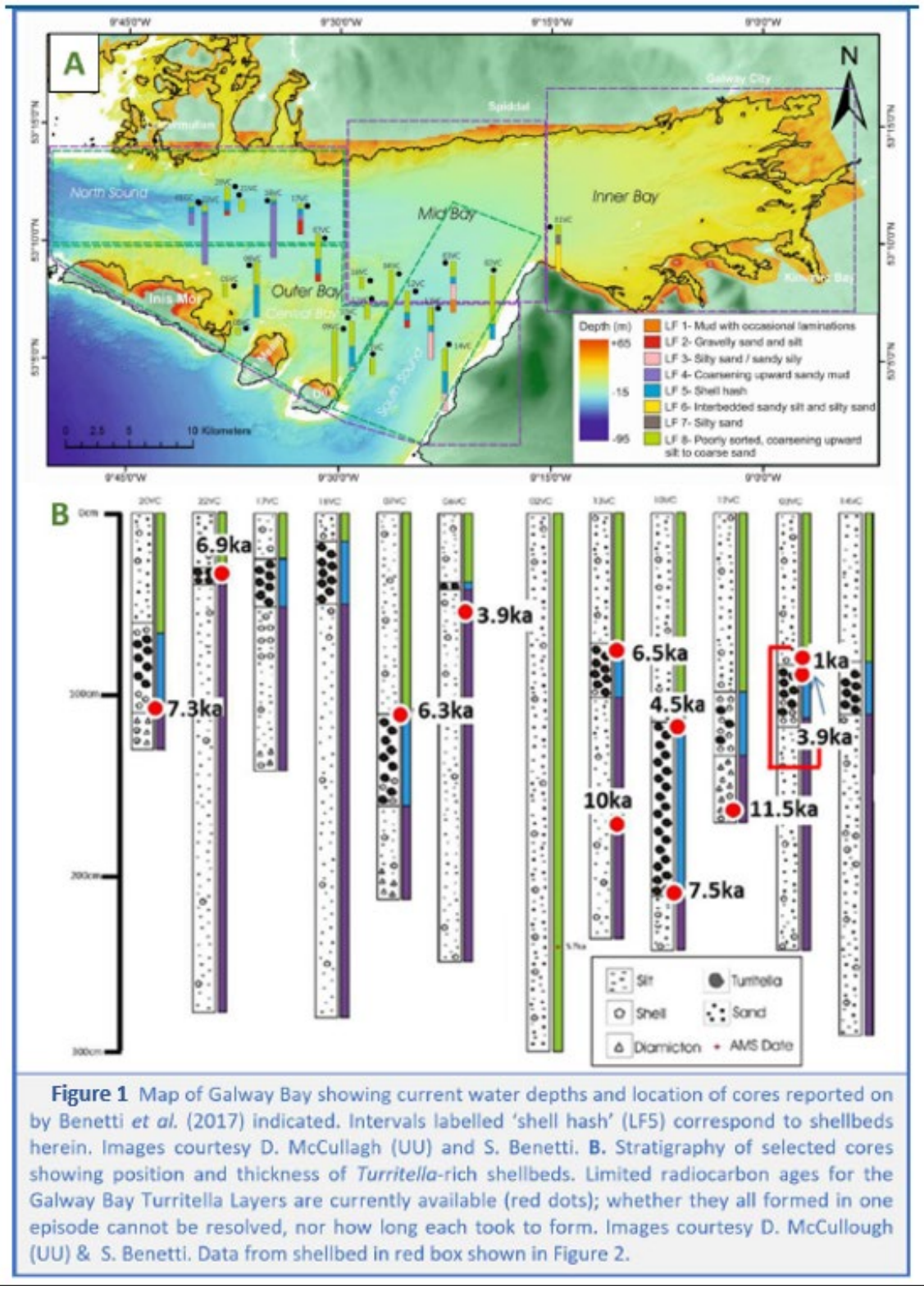


Figure 1 Map of Galway Bay showing current water depths and location of cores reported on by Benetti *et al.* (2017) indicated. Intervals labelled 'shell hash' (LF5) correspond to shellbeds herein. Images courtesy D. McCullagh (UU) and S. Benetti. **B.** Stratigraphy of selected cores showing position and thickness of *Turritella*-rich shellbeds. Limited radiocarbon ages for the Galway Bay Turritella Layers are currently available (red dots); whether they all formed in one episode cannot be resolved, nor how long each took to form. Images courtesy D. McCullough (UU) & S. Benetti. Data from shellbed in red box shown in Figure 2.

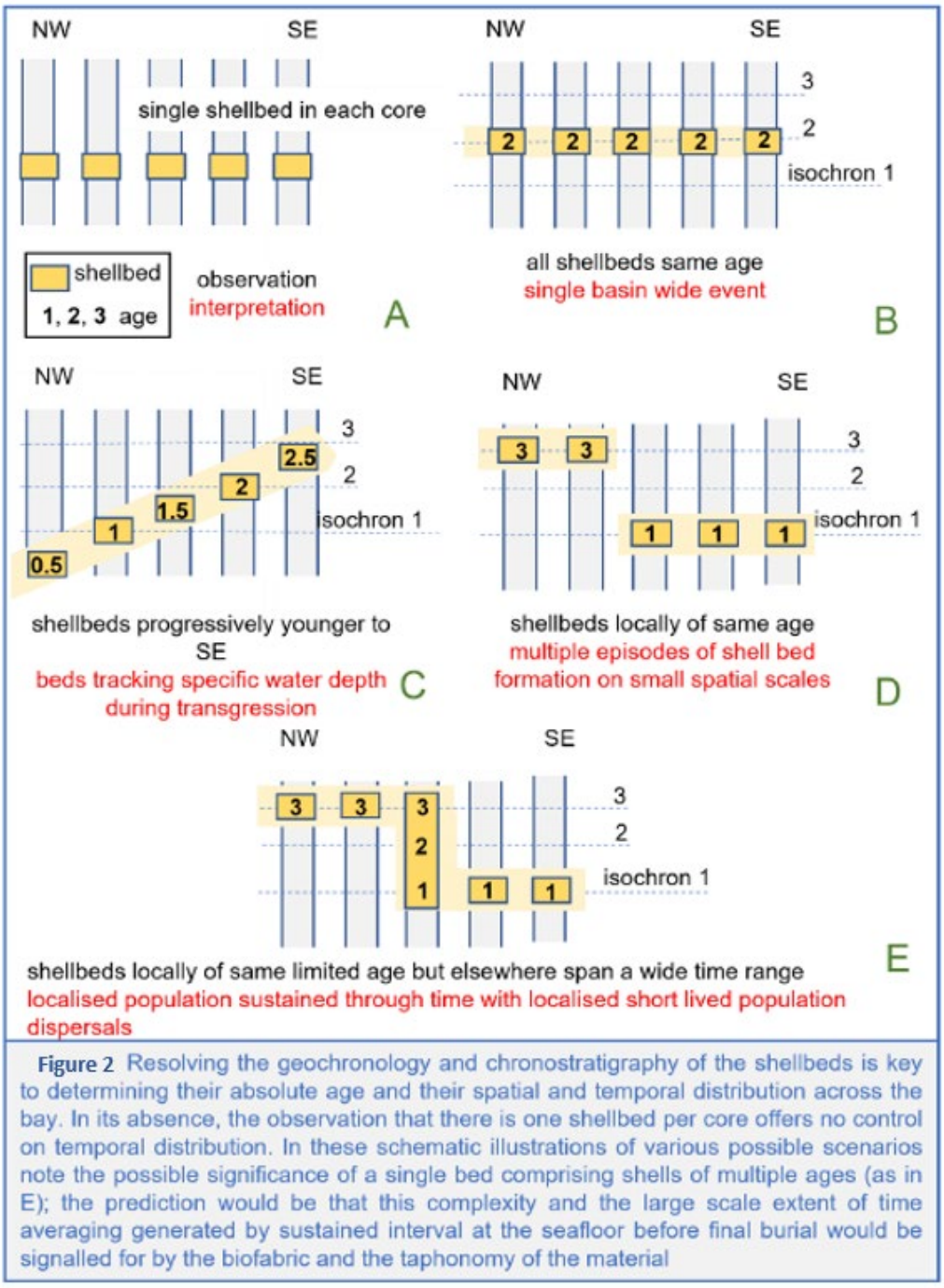


Figure 2 Resolving the geochronology and chronostratigraphy of the shellbeds is key to determining their absolute age and their spatial and temporal distribution across the bay. In its absence, the observation that there is one shellbed per core offers no control on temporal distribution. In these schematic illustrations of various possible scenarios note the possible significance of a single bed comprising shells of multiple ages (as in E); the prediction would be that this complexity and the large scale extent of time averaging generated by sustained interval at the seafloor before final burial would be signalled for by the biofabric and the taphonomy of the material

(ii) Implementation (milestones, deliverables, project management)

Implementation: Project Objectives

To test the hypothesis two scientific targets were defined.

A: provide the first description of the structure of shellbeds at sufficiently high stratigraphic resolution to identify changes in taphonomy, taxonomy and ecology through, and between, shellbeds.

B: identify the processes responsible for the shellbeds' formation, including testing whether the GBTLs satisfy the criteria to be considered palaeocommunities

(1) Selected cores were logged at centimetre-scale using standard methodologies.
(2) Logging provided information that informed selection of key cores for CT X-ray scanning using the facilities of the UCD Rosemount, Environmental Research Station, to obtain the x-ray image stacks necessary for 3D imaging of selected cores.
(3) Three dimensional virtual reconstructions of the shellbeds' structure from the micro-CT images, and data derived them were acquired using Dragonfly software, Version 2020.2 for Windows, Object Research Systems (Dragonfly ORS) Inc, Montreal, Canada, 2020; software available at http://www.theobjects.com/dragonfly. We gratefully acknowledge ORS for permission to use their software.
(4) Physical sampling in 10mm increments was undertaken for two Galway Bay cores, 13VC and 03VC, to (1) establish the taphonomy of individual shells; (2) determine the taxonomic composition of the fossil assemblage; (3) observe any microscopic grain size changes, and archive the host sediments (4) recover and archive any micropaleontological content. The processes are destructive, but provide data that cannot be recovered via micro–CT X-ray (as the components are below the resolution of the images). In addition, the intention was to ground truth the CT data, and establish if CT scanning alone would be sufficient to identify and quantify the bioclastic component of the remaining Galway Bay cores.
(5) The relative and absolute ages of the shellbeds were using a combination of amino acid racemization (a low-cost relative dating method) calibrated to radiocarbon ages (absolute age); the latter are not, as yet, available (instrument failure). Funding permitted a comparison of the ages of the shells in cores 13VC and 03VC.

Implementation: Project management

Day to day effort and management was principally by the Research Assistant (Rachel Healy) with oversight from the PI on an on-going basis; regular, episodic, meetings were held to discuss progress, and design and implement the next phase of the research.

Implementation: Results and Deliverables

1. Sedimentary Logging

Cores were logged at cm-scale (Figure 3), with particular focus on the structures and thickness of the GBLTs (as detailed in Table 1). The key observations were:
Three types of shell beds were identified; *Turritella* Shellbeds; Bivalve Shellbeds; and, Mixed *Turritella*- Bivalve Shellbeds.
Turritella Shellbeds and Bivalve Shellbeds are distinct from the Mixed Shellbeds as their composition is near-monospecific – (i.e. either *Turritella* or bivalves) and they have sharply defined upper and basal contacts.
Turritella shells are largely intact, tend to lie horizontal relative to the core and have a size range 0.5-5cm, with 1-3cm being most commonly observed.
Packing patterns show some variation between cores (Table 1), with thicker shellbed intervals more likely to show variation.

Core	Thickness (m)	Shellbed Thickness (m)	Average Shell Size (cm) and Sorting	Packing Patterns	Fragmentation	Orientations	Shellbed contacts
03VC Mixed Turritella Bivalve Shellbed	2.35m	0.5m	Turritella shells range from poorly sorted, 1-3cm at the base of the shell bed to well sorted, 0.5-1cm at the top of the shellbed. Bivalves range from 2-4cm at the base and decrease in size upwards.	The shellbed becomes more densely packed upwards to a maximum in at the centre of the bed before becoming less densely packed towards the top.	Largely intact at the base of the shell bed, becoming more fragmented in the top 5cm of the bed.	Largely horizontal, with some oblique apex up orientated turritella.	Both the bottom and the top contacts of the shellbed are gradational, with a concentration of large (2-4cm) bivalves at the base. There is an increase of grainsize from underlying sediments.
07VC Bivalve Shellbed	2.13m	1.0m	Shell bed is dominated by large (7-10cm long) oyster shells surrounded by poorly sorted bivalves (0.5-3cm). Absence of Turritella	The shellbed is moderately packed, becoming more densely packed upwards.	The larger oyster shells are intact but surrounded by heavily fragmented bivalve shells.	Oyster shells have an oblique orientation relative to normal of the core.	Both boundaries to the shell bed is transitional with no grainsize changes.
10VC Turritella Shellbed	2.25m	0.95m	The turritella shell size increases gradually from 0.5-1 cm at the base to 2-3cm at the top of the shell bed. Some small (0.5-1cm) bivalves are present.	The packing of this shellbed shows subtle variations over the thickness of the bed. Although densely packed some intervals of the bed appear less densely packed.	Largely intact throughout the bed, some minor fragmentation in the form of missing apex tips. Bivalve fragments are incorporated in the surrounding sediment.	Largely horizontal, with some oblique apex up orientated turritella.	The basal contact is marked by change in grainsize and abrupt presence of intact Turritella. The top of the shellbed becomes increasingly bivalve dominated.
13VC Turritella Shellbed	2.41m	0.35m	Turritella shell size is relatively consistent throughout the shellbed, ranging 1-3cm, with bivalves 0.5-1.5cm.	The shellbed is densely packed, with possibly less densely packed shell halfway through the shellbed.	Majority of Turritella are intact, with increased fragments present towards top of bed.	Largely horizontal, with some obliquely orientated Turritella	The base and top contact of the shellbed is relatively sharp and marked with abrupt appearance of Turritella and sharp grainsize increase.
14VC Bivalve Shellbed	2.88m	0.13m	Predominantly, poorly sorted, individual bivalve shells, 0.5-2.5cm. There is an absence of turritella.	The shellbed is relatively densely packed compared to underlying and overlying sediments	Bivalves high highly fragmented above and below the shell bed. The shellbed has majority intact bivalves	Some bivalves show a subparallel, horizontal orientation relative to the core normal.	Contacts between shellbed and other sediments are subtle and transitional. The separation is observed due to decreased fragmentation and increased shell size.

Core	Thickness (m)	Shellbed Thickness (m)	Average Shell Size (cm) and Sorting	Packing Patterns	Fragmentation	Orientations	Shellbed contacts
17VC Turritella Shellbed	1.42m	0.4m	Turritella shells average 1-3cm, with subtle decrease in shell size upwards.	Densely packed throughout. No observable changes.	Little to no fragmentation, some minor damage to shell apexes	Largely horizontal, with some oblique apex up orientated turritella.	The basal contact is marked by abrupt presence of turritella and a large grainsize increase causing it to appear almost erosional. The top of the bed transitions into fragmented bivalves
18VC Turritella Shellbed	2.79m	0.3m	Turritella shells are poorly sorted with a small increase in size upwards (0.5-5cm).	Densely packed throughout. No observable changes.	Decreasing fragmentation upwards in shellbed. Fragmentation still at a minimum.	Largely horizontal, with some oblique apex up orientated turritella.	The basal contact is marked by a change in grainsize and present of shells. The top of shellbed is sharp.
20VC Mixed Turritella Bivalve Shellbed	1.32m	0.5m	The base of the shell bed is dominated by 0.5-3cm, poorly sorted bivalves and lithoclasts (0.5-2cm). The Turritella dominated interval is also poorly sorted, with intact shells ranging from 0.5-4cm.	The packing varies up the core and with predominant shell type. The turritella appear more densely packed than the bivalves and lithoclasts.	Fragmentation is increased both below and above the Turritella interval.	Largely horizontal, with some oblique apex up orientated turritella	The contacts between the different compositional shellbeds are extremely subtle.
22VC Turritella Shellbed	2.86m	0.15m	1-3cm intact relatively well sorted Turritella shells.	Densely packed throughout. No observable changes	Little to no fragmentation, some minor damage to shell apexes	Largely horizontal, with some oblique apex up orientated turritella	The base and top of the shellbed are sharp and mark a change in grainsize.

Table 1. Summary of observations on the structure of shellbeds made during logging of cores from Galway Bay. Key parameters studied were: shell size variation, density of shells, degree of fragmentation. Limited detail on shell orientation is possible from the two dimensional surface of the core: the orientation of the shell apex (up/down relative to core way up) and shell inclination (horizontal versus inclined) were noted. The nature of the boundaries between each shellbed and the sediment were recorded. Cores highlighted in yellow were chosen for CT scanning.

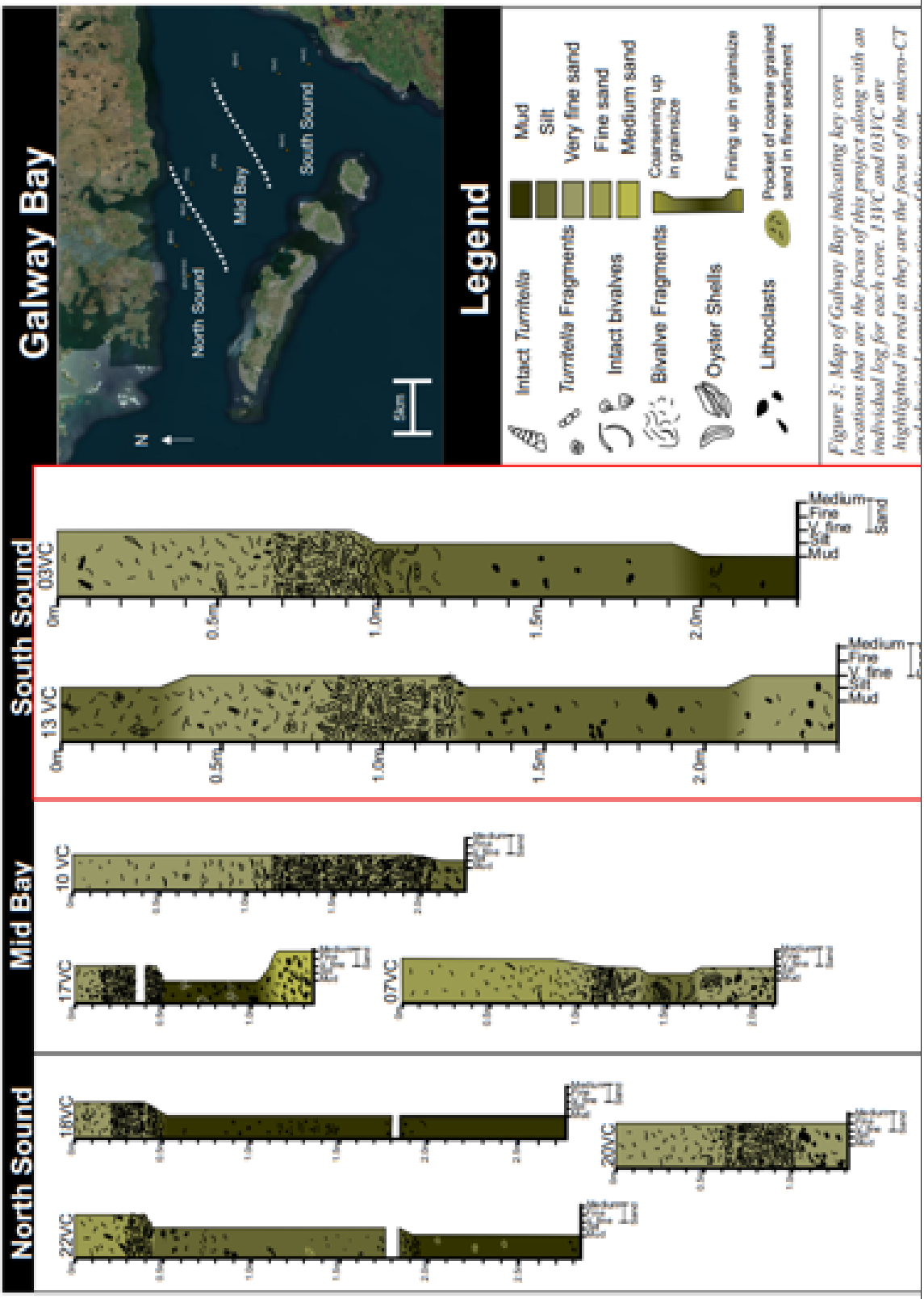


Figure 3. Map of Galway Bay indicating key core locations that are the focus of this project and a sedimentary log of each core. 13VC and 03VC (highlighted in red) were the focus of analysis of the CT data and physical sampling.

2. 3D reconstructions

3D reconstructions of intervals spanning the GBTL were completed for each core to visualise the biofabric. The distinctive shape of *Turritella* lends itself to investigating how the shells are oriented in 3D (their biofabric), which may be indicative of the processes responsible for the shellbeds' formation (Figure 4). In Dragonfly ORS the volume of a shell is measured from the number of voxels it is composed of and expressed in mm3. The volume of each (entire) shell is a proxy for its size; thus the structure of the assemblage and whether it maps to that expected of a population can be quantified. Dragonfly can measure the relative orientation of an object (i.e. a *Turritella* shell) to the z axis using two angles, phi and theta, similar to angles used in circular co-ordinate systems (Figure 4). Phi is the object's inclination: the angle of the object away from the z axis, between 0-90 degrees where 0 is vertical and 90 is horizontal. Theta is the object's declination: the rotation of the phi angle around the z axis, between 0-360 degrees (Figure 4). The 3D reconstructions and Dragonfly ORS were used to assess both the volume and orientation of individual *Turritella* (e.g. Figure 5). To date cores 03VC and 13VC have been used to quantify elements of the *Turritella* biofabric from these reconstructions; the results of analysis of core 13VC are presented below.

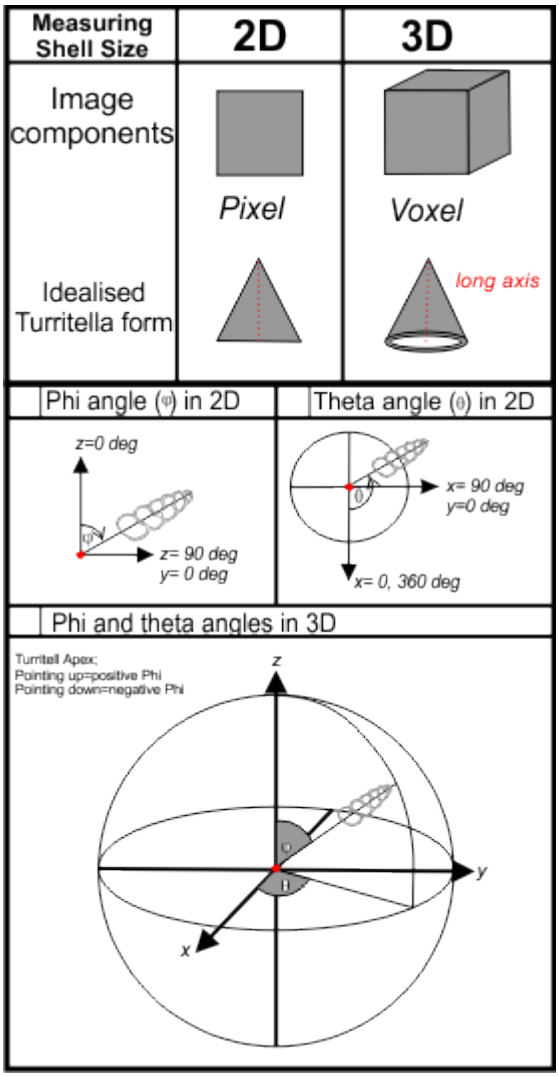


Figure 4. Theory behind measurements of volume and orientation using Dragonfly ORS.

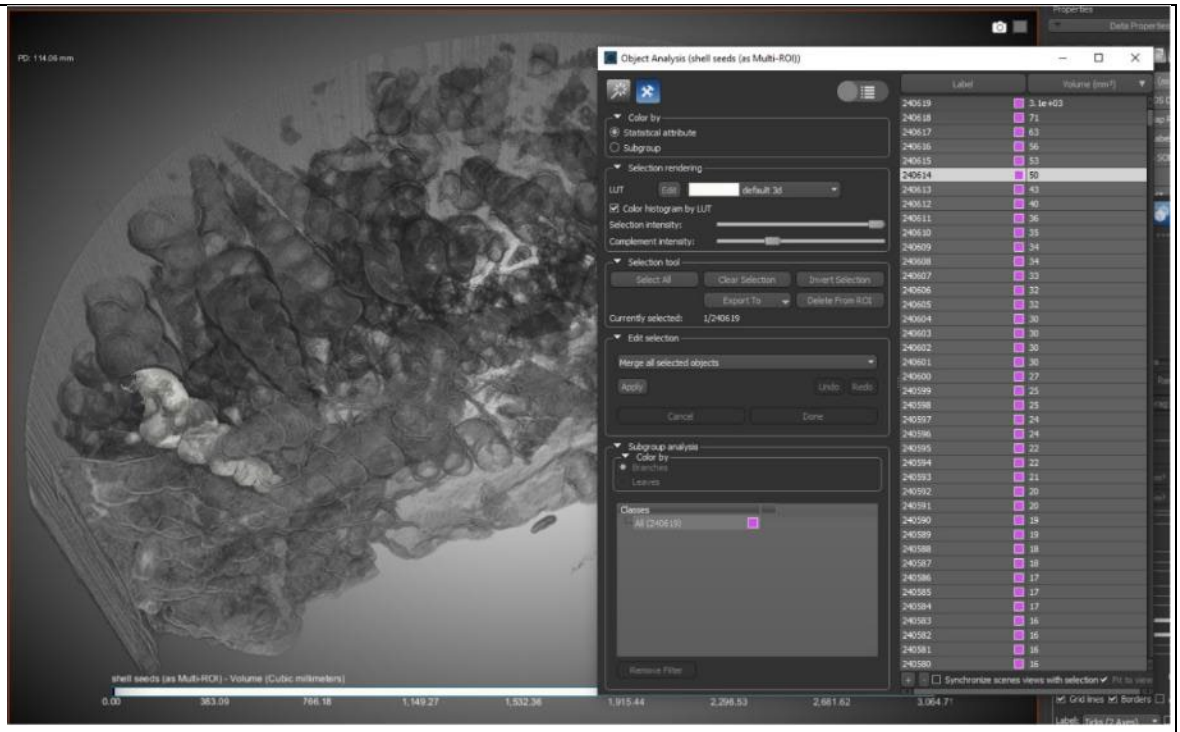


Figure 5. Individually identified *Turritella* shell, for which volume and orientation data can be recovered.

2.1 Volume calculations

Figure 6 summarises the distribution and frequency of intact *Turritella* shell volumes in core 13VC. The chart skews left indicating a larger proportion of small to moderately sized *Turritella* shells.

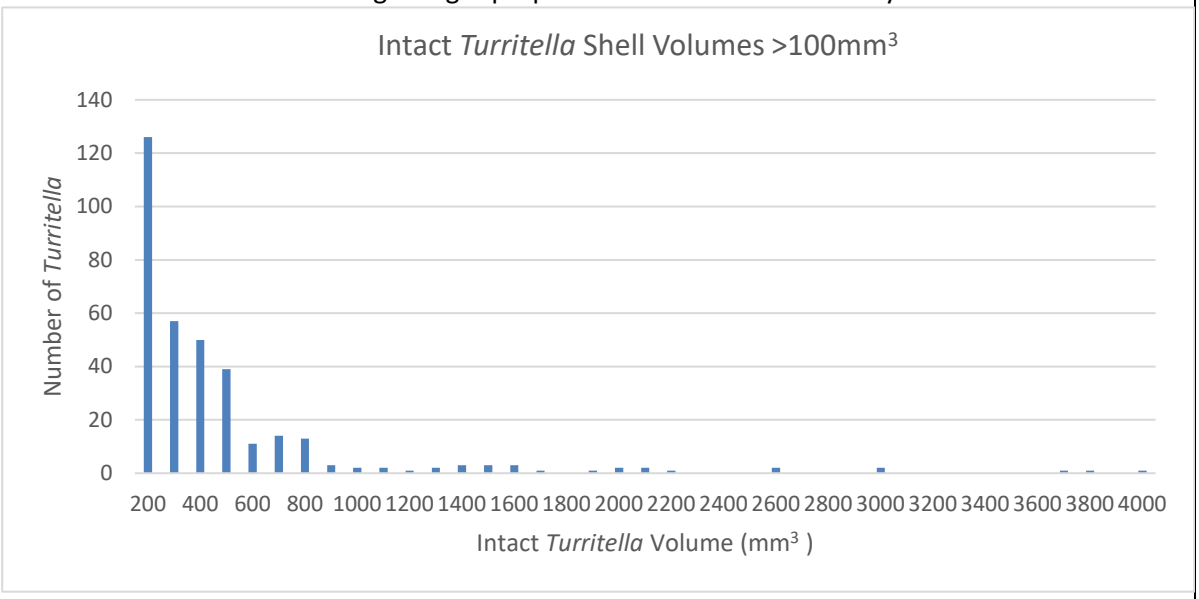


Figure 6. Distribution of *Turritella* shell volumes in mm^3 for core 13VC. (above a lower threshold of 100mm^3).

2.2 Orientation

Phi angles for intact *Turritella* greater than 100mm^3 volume for core 13VC indicate a preferred angle of sub-horizontal to horizontal (i.e. at 90 degrees to the vertical direction of the core and

broadly parallel to the seafloor) (Figure 7). *Turritella* are typically observed in this position while living (Allmon, 1988); this is also the most stable post-mortem orientation.

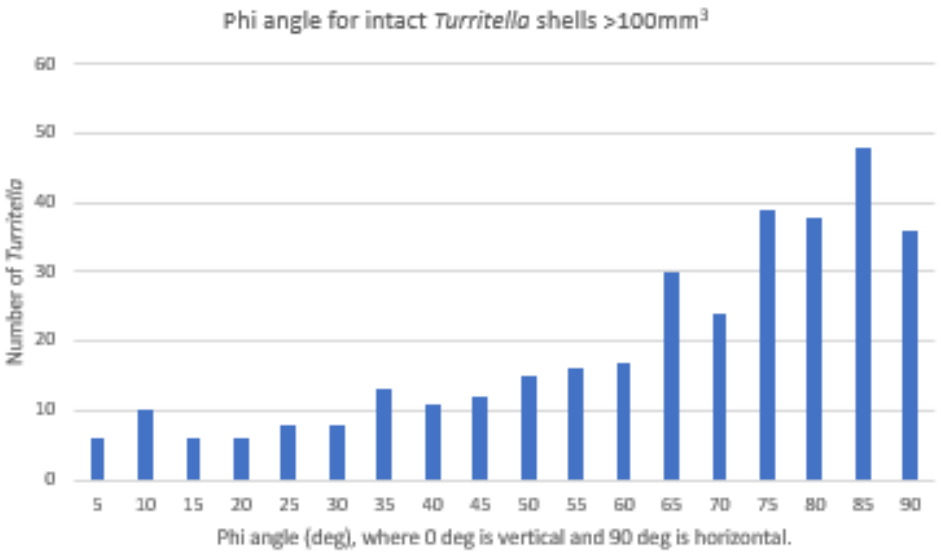


Figure 7. Distribution of Phi angles for intact *Turritella* shells above 100mm^3, indicating a preference for shells to be orientated sub-horizontal to horizontal.

In Figure 8, the theta angles for core 13VC are displayed in a stereonet. Shells are of multiple orientations, although a weak trend at 165°/345° degrees can be observed. The presence of the latter, but the presence of numerous other orientations, suggests some, but limited, reorientation of the shells by currents. The program does not define which direction the apex is pointing in, so whether the currents were unidirectional or oscillatory is, as yet, unresolved.

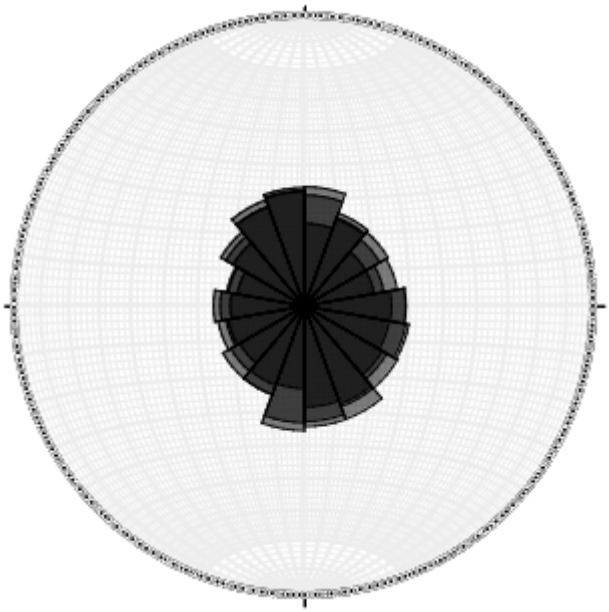


Figure 8. Theta angles for intact *Turritella* above 100mm^3/0.1cm^{3}display multiple orientations with a weak trend at 165/345 degrees.

3. Physical Sampling of 13VC and 03VC

In an effort to sample from what were likely to have been localities with similar depositional and bathymetric characteristics, cores 13VC and 03VC were used to establish the taphonomy and taxonomy of the shell beds. The two are closely spaced (both from what is now the South Sound) and a similar thickness (0.35m, 13VC; 0.5m, 03VC). There were differences identified during sedimentary logging: 03VC was a Mixed *Turritella*-Bivalve Shellbed, thus offering insight into what bivalve species were present with the *Turritella.* 13VC was classed as *Turritella* dominated shell bed during the logging process (although samples of bivalve were recovered during sampling).

3.1 Sampling Method and recording of data

One-centimetre intervals ("slices") from below, through and above the shellbeds were individually wet-sieved into different fractions (>2mm, 1-2mm, 0.5-1mm, 0.25-0.5mm and 0.25-0.125mm sieves (the finer grained component was retained)). Specimens were counted, photographed, described, and catalogued in Excel. The taphonomy of individual *Turritella* shells were recorded; the taxonomic composition of the shellbeds was established.

3.2 Taphonomy of the *Turritella* shells

Two of the most striking observations are the minimal taphonomic overprint on *Turritella* shells; and, the presence of a continuum of shell sizes in each sample. The key observations are summarised in Figure 9. Fragmentation is exclusively the result of (successful) crab predation; healed fractures are also common. The fractured edges produced via predation and the shells apices, remain razor-sharp. Both fragments and the remainder of the shell co-occur, and individual samples repeatedly show a continuous range of sizes. There is no evidence for sorting by size during lateral transport and/or reworking *in situ*. Collectively, the observations strongly indicate shells experienced minimal to no physical post-mortem reworking after the animal's death and the original population structure has been retained.

Figure 9. Summary of the key observations re the taphonomy of the material and population structure (A). B. Samples from different levels indicating same taphonomic features ad population structure persists through each GBTL. consist

3.3 Taxonomic Composition of the shellbeds

3.3.1 Bivalve Species

Fifteen bivalve species were identified below, above and inside the *Turritella* shellbeds, of which 11 were found in significant numbers (n>5 specimens) (Figure 10). The individual species were identified using reference to taxonomic literature and with the assistance of Dr Anna Holmes (National Museum of Wales).

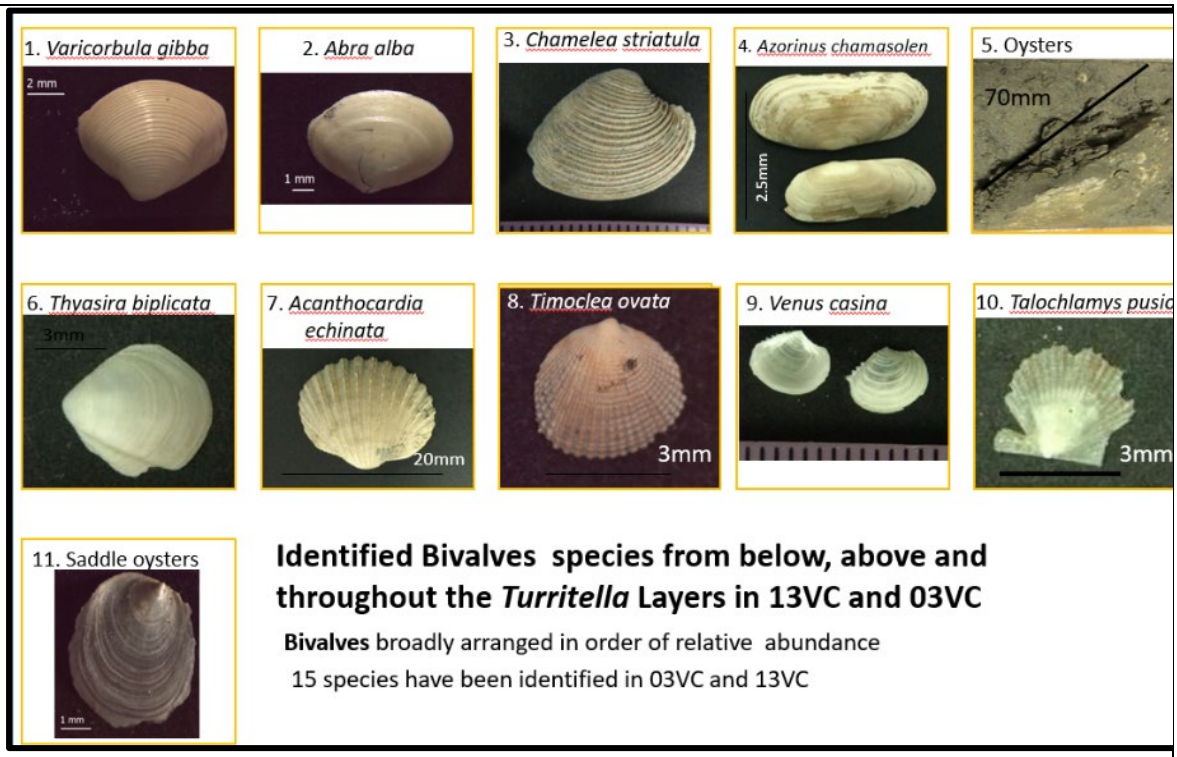


Figure 10. Photos of the 11 most significant (n>5 specimens) bivalve species recovered from 13VC and 03VC. The bivalves are broadly arranged in order of relative abundance; 1) Varicorbula gibba, 2) Abra alba, 3) Chamelea striatula, 4) Azorinus chamasolen, 5) Common Oysters (Ostrea edulis), 6) Thyasira biplicata, 7) Acanthocardia echinate 8) Timoclea ovata, 9) Venus casina, 10) Talochlamys pusio, 11) Saddle oyster (Pododesmus squama).

The most common bivalves were *Varicorbula gibba, Abra alba* and *Chamelea striatula*, which are found throughout each core. Large oyster shells (original length 70-80mm) occur below and partially overlapping with the *Turritella* layer in 03VC.

The distribution of the different taxa through each shellbed is shown in Figure 11. Three taxa are more common than the others, and occur consistently through much (03VC) or all (13VC) of each core (*Varicorbula gibba*; *Abra alba*; *Chamelea striatula*). These are shallow-marine infaunal species usually associated with muddy to silty sand, that occur in inter-tidal to sub-tidal, fully saline conditions (30-35 PSU) and waters of 10-15 degrees Celsius. (Ocean Biodiversity Information System (obis.org), WoRMS - World Register of Marine Species, Home | Marine Bivalve Shells of the British Isles (museumwales.ac.uk)).

There are differences between the biodiversity of each core, despite their being closely spaced. 13VC shows little change in diversity and the relative abundance of taxa over the interval studied, which spans the GBTL, and both above and below it. In contrast the faunal distribution in 03VC is more complex.

The lower part of the 03VC GBTL and the immediately underlying sediments contain oysters (Figure 11 column 5). The lower part of the GBTL, but not the underlying sediments, contain other bivalves (*Thyasira biplicata, Acanthocardia* echinate, *Timoclea ovata, Venus casina, Talochlamys pusio*; Figure 11). *Abra alba, Chamelea striatula and, in particular, Varicorbula gibba,* which recur continuously elsewhere in the core, are notably rare in the part of the succession below the GBTL, and essentially absent in the part in which oysters are present.

Oysters are a taxon that *can* be intertidal to shallow subtidal and euryhaline. It could be informative to date some of the oyster material in the 03VC GBTL to see if it is the same age as, or older than, the stratigraphically equivalent *Turritella*. In the latter scenario, the oyster material could have been incorporated into younger sediments as, in turn, the transgression continued, fully marine conditions become established (hence the increase in diversity (the additional bivalve taxa)), and subsequently the conditions favouring *Turritella* became prevalent, accompanied by a loss of diversity).

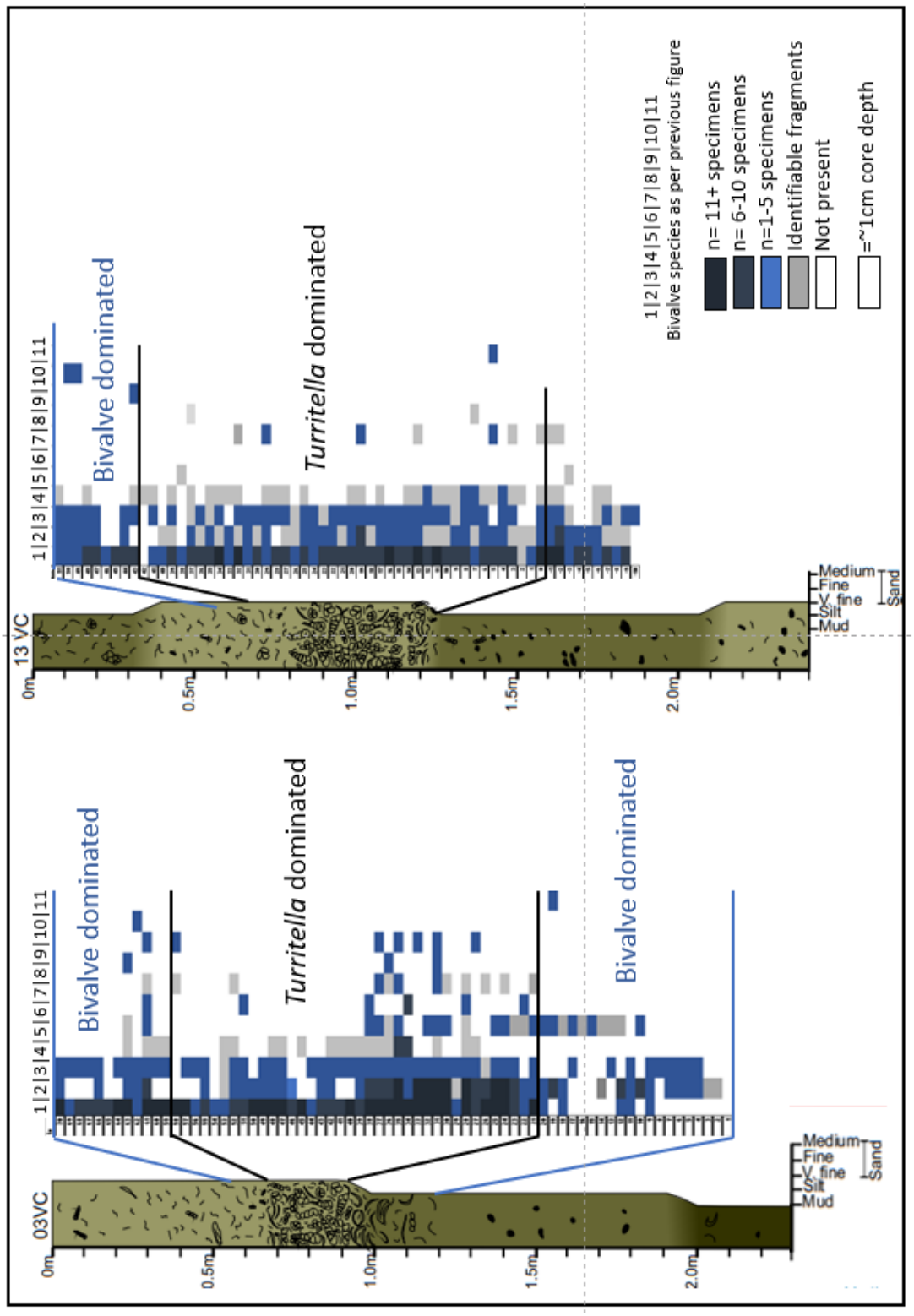


Figure 11: The stratigraphic distribution and relative abundance of the 11 most significant bivalve species below, above and throughout the *Turritella* layers in 03VC and 13VC. Numbers 1-11 correspond to images in Figure 10; *1) Varicorbula gibba, 2) Abra alba, 3) Chamelea striatula, 4) Azorinus chamasolen, 5) Common Oysters (Ostrea edulis), 6) Thyasira biplicata, 7) Acanthocardia echinate 8) Timoclea ovata, 9) Venus casina, 10) Talochlamys pusio, 11) Saddle oyster (Pododesmus squama).*

The bivalves displayed similar taphonomic features to the *Turritella* specimens. Specimens exhibit no evidence of abrasion, edge rounding bioerosion and encrustation; levels of fragmentation are low, except for *Abra alba*, which we attribute to the extreme fragility of these specimens; most of the fragmentation of these may be post-burial. Likewise we suspect post-burial fragmentation of the oysters and/or during recovery of the cores (large, relatively thin and plate-like) may have occurred.

3.3.2 Micropaleontology

Ostracods

Only one well-preserved species of ostracod (*Pterygocythereis jonesii* (BAIRD, 1850). (WoRMS - World Register of Marine Species)) was observed in significant numbers (n=373) in 03VC and 13VC (Figure 12(1)). *P. jonesii* is a common marine ostracod species associated with saline conditions (s 34-35 PSU), fine-silty sand and a wide geographic distribution, across the Mediterranean (Bonaduce et al., 1975), the Black Sea (Williams, 2012) the Algarve, Portugal (Cabral et al. 2011), Great Britain (Baird, 1850) and the North Sea (Penny, 1993), demonstrating a broad tolerance of seawater temperatures. The reason for the lack of biodiversity displayed by the ostracods is, as yet, unknown.

Foraminifera

Twelve diverse species of benthic foraminifera (n=94) were identified (Figure 12 (3-14)); the most common were *Ammonia bravata* (n=42) and *Quinqueloculina seminulum* (n=23) (Figure 12 (3-4)). These species are usually associated with fully saline conditions (30-35 PSU) and 10 to 20 degrees Celsius water temperature. They are commonly found in shallow-marine environments similar to the bivalve species identified. (Ocean Biodiversity Information System (obis.org) , WoRMS - World Register of Marine Species).

Two species, *Elphidium* and *Nonionellina labradorica* in 03V are recognised cold-water species, often associated with glacial conditions (Jennings et al. 2004, Wood et al. 2018). The only previous recording of *Nonionella labradorica* in Irish marine sediment cores is by Wood et al. (2018), associated with the Younger Dryas climate event (approximately 12,000 cal BP). As they were not found in significant numbers (n<10) and occurred at the base of the *Turritella* Layer it is possible these taxa were sourced from the underlying sediments. McCullough (2019) identified a diamictite-type deposit underlying the Holocene sediments of Galway Bay which could be the origin of these species.

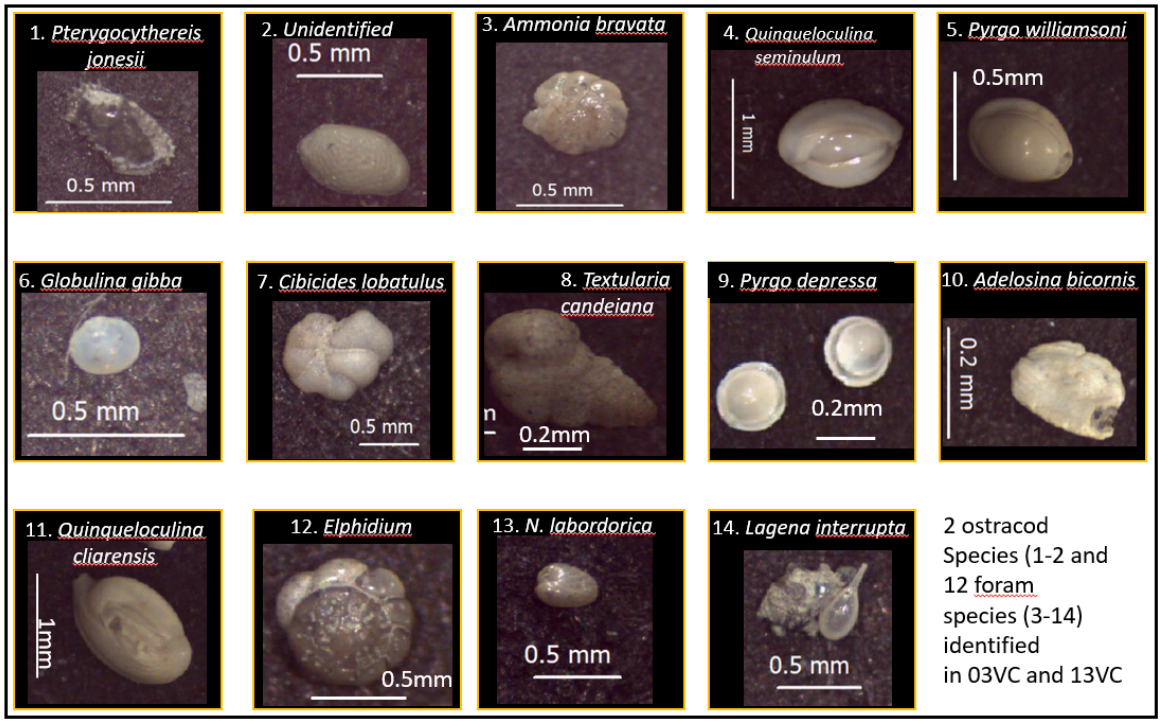


Figure 12. Micropalaeontological specimens recovered form 03VC and 13VC. Ostracod species; 1. *Pterygocyereis jonesii* and 2. as yet unidentified. Formanifera; *3. Ammonia bravata, 4. Quinqueloculina seminulum, 5. Pyrgo williamsone, 6. Gobulina gibba, 7. Cibicides lobatulus, 8. Textularia candeiana, 9. Pyrgo depressa, 10. Adelosina bicornis, 11. Quinqueloculina cliarensis, 12. Elphidium sp. 13.Nonionellina labradorica 14. Lagena interrupta.*

4. Dating the GBTL in 13VC and 03VC via radiocarbon dating and amino acid racemization.

Selected *Turritella* specimens spanning below, through and above the *Turritella* layers of cores 03VC and 13VC have been radiocarbon dated, and their amino acid composition determined (NAU, Flagstaff, Arizona USA). Amino acid racemization is a relative dating technique; the principles are summarised in Figure 13.

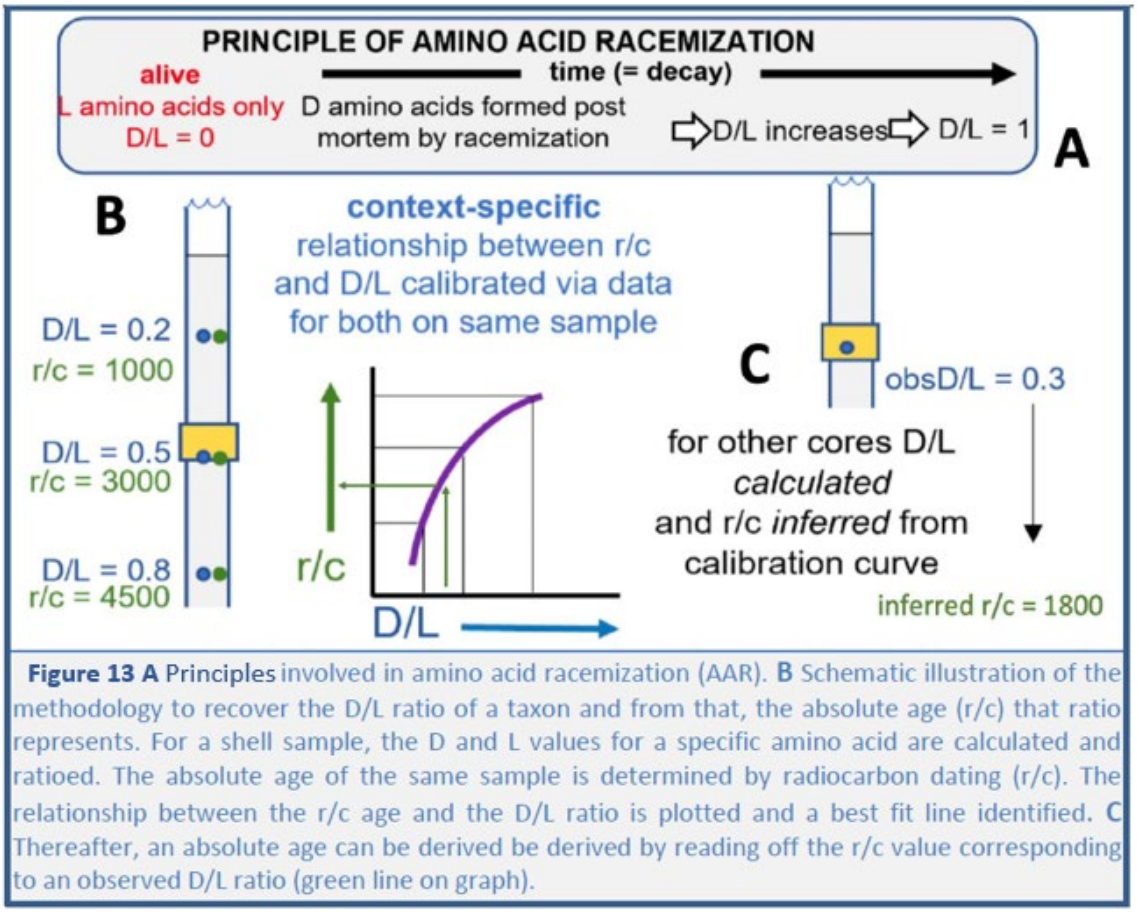
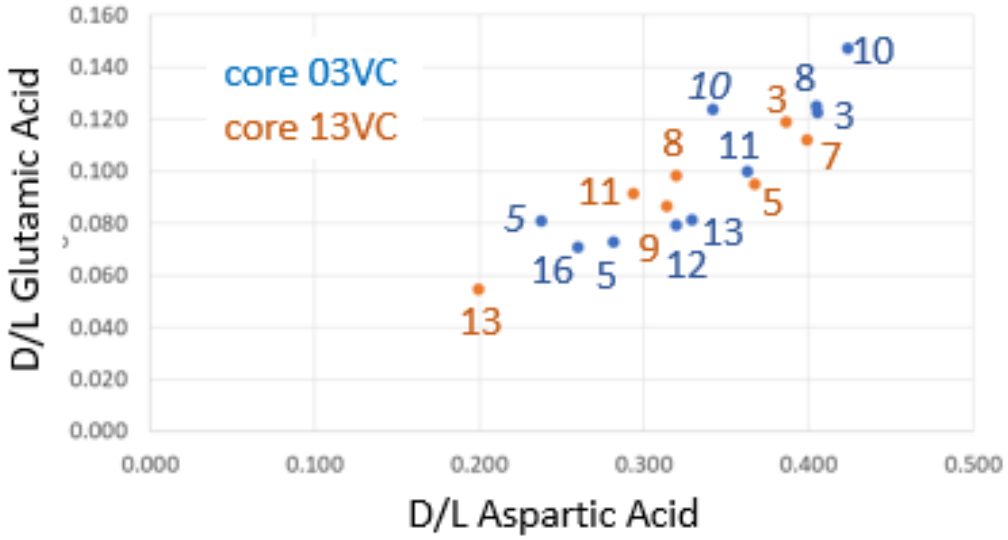


Figure 13 A Principles involved in amino acid racemization (AAR). **B** Schematic illustration of the methodology to recover the D/L ratio of a taxon and from that, the absolute age (r/c) that ratio represents. For a shell sample, the D and L values for a specific amino acid are calculated and ratioed. The absolute age of the same sample is determined by radiocarbon dating (r/c). The relationship between the r/c age and the D/L ratio is plotted and a best fit line identified. **C** Thereafter, an absolute age can be derived be derived by reading off the r/c value corresponding to an observed D/L ratio (green line on graph).

The preliminary AAR results (Figure 14) for shells from cores 03VC and 13VC display an overlap for data from each core; this implies the two shellbeds are the same age. There is reasonable ordering of the values in relation to stratigraphic position (compare observed versus expected values in Figure 14). This is encouraging as it suggests much of the original stratigraphy has been retained and physical processes or bioturbation have not thoroughly mixed the sediments. Excluding sample 03VC/5 which shows a marked translation upwards from the stratigraphic position expected, most deviations from the order expected are limited, involve translation downward and occur at the base of the *Turritella* layer (013VC/7 and 03VC/10).



core 03VC expected 3 5 8 10 11 12 13 16
observed order 10 8 3 *10* 11 13 12 5 16 *5*

core 13VC expected 3 5 7 8 9 11 13
observed order 7 3 5 8 9 11 13

Figure 14. D/L ratios for Aspartic and Glutamic Acid for cores 03VC and 13VC. 'expected' lists the samples in ascending stratigraphical order by sample number and 'observed' by relative position in the x-y plot. Alternate values for samples 03VC5 and 03VC10 shown on plot; rejected values in *italics*.

Interim Conclusions

The following interim conclusions are based on the two cores analysed in detail.

(1) The taphonomy of the GBTLs in 03VC and 13VC strongly supports their being *in situ* (autochthonous) well preserved palaeocommunities. Post mortem taphonomic modification of the shells generally, and *Turritella* in particular, is essentially absent; there is no evidence for extensive reworking during transport, prolonged exposure at the seafloor, or admixture of different communities.

(2) The results of radiocarbon dating (pending) will resolve the absolute age of the GBTLs in cores 03VC and 13VC. Based on their having similar D/L Glutamic Acid to G/L Aspartic Acid ratios they have the same age. This is not unexpected; they are closely spaced. Whether this applies to the remaining shellbeds remains unknown.

(3) Why the shellbeds formed when they did remains unknown. Sedimentary structures are not well developed and there are no obvious changes in lithology through the succession in each core.

(4) The environmental setting in which the shellbeds formed is not fully resolved; the bivalve fauna and foraminifera are not diagnostic of any specific water depth. It is difficult to reconcile the different strands of indirect evidence available as regards the environmental setting.

(iii) Outputs to date

1. Cores fully logged, described, and digitised. The cores are currently stored under refrigeration in UCD School of Earth Sciences and are available for viewing on request of Drs Patrick J. Orr and

Sara Benetti. Scans of the original log sheets and observations have been included in the Supplemental information section of this report.
2. Full 3D models of key sections of core that have been scanned using a micro-CT scanner at UCD Rosemount. The original scans and resulting 3D models have been stored on a hard drive and will ultimately be uploaded to MorphoSource (MorphoSource), a 3D open access data repository for researchers to store, share and distribute 3D data.
3 All cores have been segmented using a U-net model, further processed using a watershed transform and are ready for quantitative analysis. Only 03VC and 13VC have had the quantitative data extracted. That data has been recorded in Excel sheets and with the original CT scans on multiple hard drives as well as part of the DragonflyORS organiser; a feature in Dragonfly that allows quantitative measurements to be stored on their network.
4. Interim report for GSI submitted.
5. Complete physical sampling of 13VC and 03VC to compare with micro CT data. These samples are labelled, photographed and stored at present, in UCD Palaeobiology Laboratory. Samples will be retained here and used as part of a funded PhD project for further analysis eg stable isotope analysis, radiocarbon dating and sclerochronology.
6. All procedures undertaken, photographs and quantitative measurements from the physical sampling of the cores (e.g. species counts, shell measurements) have been electronically recorded in Word documents, Excel sheets, stored on hard drives and further backed up on an online electronic laboratory notebook (SciNote ELN: Electronic Lab Notebook & Inventory Management). This data is available on request.
7. Final report for GSI submitted.
8. Preliminary results arising from the Short Call funding were used to leverage further funding via: (a) the 2022 GSI Short Call (2022-2023) for the project: "*Testing the potential application of a novel geochronological technique to resolving Holocene stratigraphy offshore Ireland.*" (b) iCRAG funding (2022-2026) for a PhD (provisionally) titled "*Learning from the past to help inform the future ecological health of shallow marine ecosystems in the Anthropocene."*

(iv) Impact

The project: i) confirmed the feasibility of the GBTLs to inform on the Holocene environmental history of Galway Bay, ii) produced a comprehensive analysis of the biofabric, taphonomy and ecology of shellbeds from two key cores (objective A); iii) resulted in an initial model for the formation of the shellbeds (objective B); iv) upskilled an ECR (who subsequently secured a PhD position); v) provided an essential platform from which to leverage significant further funding to develop the research theme further; and, vi) began the process of establishing a community of practitioners researching this area.

The follow up studies funded will integrate geohistorical data and data from living communities to test for the scale of any changes in the composition of marine communities in the recent past, potentially in response to anthropogenic stressing of the marine environment. This approach is highly relevant to a diverse group of stakeholders from both the geosciences and marine sciences. Further, using geohistorical data to assess the scale of ongoing ecological issues is a relatively new methodology the potential relevance of which to management of Irish coastal ecosystems is untested.

Radiocarbon dating via AMS is relatively expensive (at least x2 the price of relative dating via AAR). The project "*Testing the potential application of a novel geochronological technique to resolving Holocene stratigraphy offshore Ireland"* will produce radiocarbon-calibrated AAR dating schemes using different amino acids for three common marine taxa from the Holocene of Galway Bay. To

span the Holocene a combination of fossil specimens from through the cores and living (at the time of collection) and dead specimens from the tops of the cores and surficial grab samples (collected by the Marine Institute in January 2023) will be used. This study offers the possibility of reconstructing detailed stratigraphies at low cost and high temporal resolution for successions offshore Ireland; the methods are relevant to studies seeking highly-resolved reconstructions of offshore Holocene geological histories.

On the RA's initiative, the project utilised automated 3D reconstructions incorporating machine-learning-based image segmentation techniques. These methods are widely relevant to Earth Scientists and marine scientists studying cores or other 3D objects (e.g. push cores from unsieved grab samples) the internal structure of which needs to be visualised. The methods will be refined in the course of on-going studies, initially to model the biofabric of the remaining GBTL shellbeds. Quantitative analysis of shells (their dimensions and volumes) is feasible; with further development vector rather than trend data for their orientation should be possible. Higher resolution CT scans (and thus improved training datasets) may allow the detection and analysis of smaller objects than at present. The methods will be presented at a BOSCCORF Training Course on Non-Destructive Core Logging in November 2022, and we are seeking collaboration with others to refine them further.

- Relevance/application to GSI programmes, where applicable

We envisage each of the three themes outlined above that are being progressed further will have relevance to various individuals in GSI and geoscientists elsewhere in Ireland. There are potential synergies with the GSI research themes of climate research and marine and coastal research in particular.

Publications:

Poster presentations at:
(i) Irish Geological Research Meeting, (February 2022: see https://www.gsi.ie/en-ie/events-and-news/events/Pages/IGRM-2022.aspx);
(ii) BOSCCORF Training Course *Non-Destructive Core Logging* (November 2022);
(iii) iCRAG 2022 Research Showcase (December 2022).

Public Engagement presentation at GSI Researchers' night, NUI, Galway (October 2022).

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