

1 Maximum extent and dynamic behaviour of the last British-Irish Ice Sheet west  
2 of Ireland

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8 **Abstract**

9 A complete reconstruction of the last British-Irish Ice Sheet (BIIS) is hindered by uncertainty  
10 surrounding its offshore extent and dynamic behaviour. This study addresses this problem by  
11 reconstructing the depositional history of four sediment cores taken from a series of sinuous  
12 glacial sediment ridges on the continental shelf west of Ireland. We present new geomorphic,  
13 sedimentary and micropaleontological data that record a maximum westward BIIS extent that was at  
14 least 80 km farther offshore from any previous estimates. The data suggests that a large ice shelf  
15 formed over parts of the shelf prior to retreat. This new data increases the areal extent of grounded  
16 BIIS ice by ~6,700 km<sup>2</sup> from previous estimates, which represents a ~3% increase in the Irish Sector  
17 of the ice sheet. Three new AMS radiocarbon dates demonstrate for the first time that the BIIS  
18 advanced to the shelf edge during last glaciation (Late Midlandian/Late Devensian), with ice advance  
19 onto the Porcupine Bank occurring after 24,720±260 yr Cal. BP. Deglaciation was complete by  
20 19,182±155 yr Cal. BP, thus constraining BIIS occupation over the Porcupine Bank to less than 5,500  
21 years. Estimated retreat rates of marine-terminating ice across the shelf range from ~70-180 myr<sup>-1</sup>.

22 **Key words**

23 British-Irish Ice Sheet; marine-terminating ice margin; maximum extent; Porcupine Bank; continental  
24 shelf; ice shelf; radiocarbon; sedimentology; benthic foraminifera; geomorphology

## 25 **1. Introduction**

26 Despite more than a century of investigation, there remains much about the last(Midlandian)  
27 British-Irish Ice Sheet (BIIS)that is poorly understood, particularly with respect to its marine-  
28 terminating margins, whichwould likely have been crucial to ice sheet dynamicsand mass balance  
29 given the sensitivity of such margins to environmental forcing (Rott et al., 2002; Rignot et al., 2004;  
30 Scambos et al., 2004; Domack et al., 2005; Pfeffer, 2007; Pritchard et al., 2009; Glasser et al., 2011).  
31 Additionally, the BIIS has been proposed as a possible analogue for sections of the West Antarctic Ice  
32 Sheet (WAIS) (Clark et al., 2012a) that are thought to be potentially unstable (Lowe and Anderson,  
33 2003; Gladstone et al., 2012; Park et al., 2013; Ren et al. 2013), highlighting the importance of  
34 developing a better understanding of marine-based ice masses. This research is the first to produce  
35 dated sedimentary and geomorphological evidence of what is likely the westernmost extent of the last  
36 BIIS's marine-terminating margin.

37 Previous investigations of the last glaciation of the Irish continental shelf using marine  
38 geophysical data have identified large arcuate ridges north and west of Ireland (King et al., 1998;  
39 Sejrup et al., 2005; Benetti et al., 2010; Dunlop et al., 2010; Ó Cofaigh et al., 2010; Fig. 1a). These  
40 ridges were first interpreted by King et al. (1998) as end moraines (Fig. 1a) and Sejrup et al. (2005)  
41 subsequently confirmed this interpretation on the basis of seismic data. More recently, detailed  
42 geomorphic analyses have been completed on the Irish continental shelf west and north of Donegal  
43 Bay and the Malin Sea. This research has documented nested end- and recessional-moraines, lateral  
44 moraines, drumlin swarms, and extensive areas of iceberg scouring that confirm the presence of  
45 grounded, marine-terminating ice lobes on the continental shelf (Benetti et al., 2010; Dunlop et al.,  
46 2010; Ó Cofaigh et al., 2010).

47 Despite these geomorphologic advancements, no analyses of the glacial sedimentology or  
48 palaeoenvironment have been completed west of Ireland. Furthermore, no previous research has  
49 dated the advance of the BIIS onto the continental shelf west of Ireland. This research coordinates

50 new geomorphology that addresses a previously uninvestigated area of the glaciated North Atlantic  
51 margin using multibeam swath bathymetric data with sedimentary and micropaleontological data  
52 gathered from vibro-cores. This study employs these data to elucidate the chronology and behaviour  
53 of the BIIS west of Ireland. The bathymetric and sedimentary data are collected from a series of  
54 sediment ridges on the northern Porcupine Bank and Slyne Trough, offshore western Ireland, (Fig. 1b).  
55 These landforms are situated on the outer continental shelf, ~60 km northwest (i.e. farther offshore) of  
56 the large moraine offshore of County Galway (referred to in this paper as the Galway Lobe Moraine)  
57 described by Clark et al. (2012a) (Fig. 1).

58 The Porcupine Bank itself forms a dome-like westward projection of the Irish continental shelf,  
59 situated north of the Porcupine Seabight (Fig. 1). Water depths across the Porcupine Bank range from  
60 ~155-200 m bsl and it is made distinct from the continuous continental shelf by the Slyne Trough (Fig.  
61 1), a relatively low relief, N-S trending 'saddle' formed by a Mesozoic sedimentary basin (Murphy  
62 and Croker, 1992). These features constitute a relatively complex shelf bathymetry that was likely to  
63 have affected BIIS behaviour. Previous studies have investigated the evolution of cold-water coral  
64 mounds that occupy deeper water flanking the Porcupine Bank, some of which identified intervals of  
65 IRD (e.g., De Haas et al., 2009; Heindel et al., 2010; Smeulders et al., 2014); however no  
66 palaeoglaciological investigations have previously been completed on the Porcupine Bank and the  
67 glaciological significance of the IRD is uninvestigated.

68 The sediment ridges across the Porcupine Bank and Slyne Trough have not been previously  
69 studied. In this paper we present a series of data that indicate that these ridges are glacial in origin.  
70 We also present several AMS radiocarbon dates that offer the first chronologic constraints for ice  
71 advance across the shelf, which indicate BIIS advance during the last (late Midlandian) glaciation  
72 (MIS 2). This study area was selected for three reasons: (1) the origin of the ridges was unknown, (2)  
73 bathymetric data coverage is precise and complete in this area and (3) previous studies of the Irish  
74 continental margin (e.g. Benetti et al., 2010; Ó Cofaigh et al., 2010; Sacchetti et al., 2012) call into  
75 question the western extent of the last BIIS and its behaviour along its marine termini. These

76 properties allowed us to address the aims of this study, which were to: (1) identify BIIS maximum  
77 extent west of Ireland, (2) provide the first age constraints for the timing of this advance, (3) identify  
78 depositional mechanisms and ice-proximal palaeoenvironmental signals that reveal BIIS behaviour,  
79 and (4) constrain the timeframe of BIIS marine margin retreat west of Ireland.

## 80 **2. Methods**

81 This research employs multibeam swath bathymetric raster data collected by the Irish National  
82 Seafloor Survey (INSS)—now the Integrated Mapping for the Sustainable Development of Ireland’s  
83 Marine Resource (INFOMAR) programme—to investigate the western margin of the Irish continental  
84 shelf. The data were collected in 2000 and 2001 by the *RSV Siren* using a hull-mounted Simrad©  
85 EM1002 multibeam system. The data are compiled into a series of 25 m resolution bathymetric rasters  
86 using a Geographic Information System (GIS) to analyse the seafloor geomorphology and to target  
87 ridge crests and troughs for coring. The INSS data was used to create bathymetric hillshades and  
88 digital elevation models (DEMs) of the study area, which clearly reveal a series of sinuous ridges and  
89 extensively furrowed areas of seabed (Fig. 1b). Geomorphologic characterisation of the landforms in  
90 the study area is assisted by seafloor profile analyses using the ArcGIS® 3D analyst tool.

91 Four vibro-cores: CE10008\_42, CE10008\_43, CE10008\_44 and CE10008\_45 (henceforth  
92 referred to as cores 42, 43, 44 and 45, respectively), were collected during the CE10008 research  
93 cruise conducted in 2010 aboard the *RV Celtic Explorer* and are used to examine the sedimentological  
94 composition of the ridges (Table 1). Information on lithology, sedimentary structures, grain size and  
95 sediment physical properties were recorded in order to reconstruct depositional environments. X-  
96 radiographs were acquired and sediment physical properties were measured prior to splitting the cores  
97 at the University of Ulster, Jordanstown and the National University of Ireland, Maynooth,  
98 respectively. Digital x-radiographs were collected using a CARESTREAM DRX Evolution system  
99 and allow improved sedimentary structure identification. X-radiograph data are displayed as  
100 sketches in the sediment logs to characterise discernible structures and display them in a usable

101 manner. Original, representative x-radiograph examples of lithofacies are also provided. Sediment  
 102 physical properties of cores 42 and 44 were measured using a GEOTEK© multi sensor core logger  
 103 and consist of P-wave velocity, wet bulk density and magnetic susceptibility. A smoothed average  
 104 magnetic susceptibility value was calculated to allow comparisons between cores without anomalies  
 105 caused by large clasts; this was done by removing anomalously high measurements (four  
 106 measurements  $>100$  SI units  $\times 10^{-5}$  in core 42 and three measurements  $>300$  SI units  $\times 10^{-5}$  in core 45)  
 107 from the dataset and calculating the remaining data's average. Shear stress was measured with an  
 108 MCC© Impact shear vane from core centres in areas that allowed shear vane penetration without clast  
 109 contact, which yields spurious measurements. Shear strength measurement intervals are typically  $\leq 15$   
 110 cm, except where prohibited by clast abundance. Water content is calculated as the difference  
 111 between sediment wet and dry weights. Lithofacies were described visually and refined with x-  
 112 radiograph examinations. Grain size analyses (GSA) were performed via laser granulometry using a  
 113 MALVERN Mastersizer© at Trinity College, Dublin on 31 bulk sediment samples collected from  
 114 cores at intervals guided by lithofacies data.

115 Table 1: sediment core information.

Core	Latitude (N)	Longitude (W)	Water depth (m)	Core length (m)
CE10008_42	53° 46.2655'	12° 38.6542'	298.5	1.76
CE10008_43	53° 43.6649'	12° 31.4036'	312.5	1.17
CE10008_44	53° 38.9150'	12° 16.8818'	295.1	2.30
CE10008_45	53° 37.7487'	12° 08.0713'	293.7	2.94

116

117 Micropaleontological analyses were conducted on 31 one-cm slab subsamples that correlate to  
 118 the GSA sample intervals and are considered representative of the range of lithofacies in the cores.  
 119 Benthic foraminifera assemblages were examined because they are strongly influenced by local ocean  
 120 conditions (Murray, 2006). The subsamples were oven dried at  $<45^{\circ}\text{C}$  for  $>48$  hours and washed  
 121 through a  $63\ \mu\text{m}$  sieve to remove the mud fraction. Aliquots containing  $>300$  foraminiferal tests were  
 122 divided using a Green Geological© microsplitter and dry sieved to remove the  $<125\ \mu\text{m}$  fraction

123 following the recommendation of Schönfeld et al. (2012). Foraminifera <125  $\mu\text{m}$  were not counted  
124 because most foraminiferal tests below this size comprised unidentifiable fragments and recent  
125 comparative studies show that, at least for some samples, the constituents of the >63  $\mu\text{m}$  fraction  
126 identify ecological controls that are similar to the >125  $\mu\text{m}$  fraction (Mojtahid et al., 2009; Bouchet et  
127 al., 2012). Every identifiable foraminiferal test within the aliquots was documented to the species level  
128 whenever possible using an Olympus SZX16 low-power binocular microscope on all benthic and  
129 planktonic tests, primarily following the taxonomic descriptions of Murray (2003). Dominance (1-  
130 Simpson's index) and Fisher's  $\alpha$  diversity statistics were calculated on benthic foraminiferal counts  
131 using the micropaleontological software PAST 3.02a (Hammer et al., 2001) on >200 tests (cf. Thomas  
132 et al., 1995; Jennings et al., 2014). Fisher's  $\alpha$  is preferred for this study over the Shannon-Wiener  
133 index because the latter is based on relative proportions of species (Buzas and Gibson, 1969) and thus  
134 can yield spuriously high results for counts with highly dominant taxa (Dorst and Schönfeld, 2013).  
135 Fisher's  $\alpha$  relates the count of individuals to the number of species in a sample (Fisher et al., 1943)  
136 resulting in high values indicating high diversity (e.g., Samir et al., 2003). Dominance ranges from 0.0  
137 (all species are equally represented) to 1.0 (one species is absolutely dominant); therefore high values  
138 are associated with low diversity (e.g., Samir et al., 2003). Individual species counts are converted to  
139 relative abundances (RA), which standardises the data by describing counts as percentages of the  
140 sample population. The percentage of planktonic individuals (PTr) is calculated as a percent of the  
141 total foraminiferal count and can provide information on palaeo-surface productivity, although this  
142 must be considered strictly qualitatively in the absence of palaeo-water depths and differential  
143 dissolution data (Berger and Diester-Haass, 1988). The foraminiferal density is calculated as the ratio  
144 of the number of foraminifer individuals per mass of sediment >63  $\mu\text{m}$  in milligrams (mg) and reveals  
145 qualitative, comparative information on palaeoproductivity. Severely damaged tests are defined in  
146 this study as broken or abraded beyond positive recognition of species while still comprising  $\geq 50\%$  of  
147 the original material; this standard reduces the chance of over representing easily fragmented or easily  
148 recognisable (as fragments) species. Severely broken tests were counted for each sample and the  
149 severely damaged/identifiable test ratio (SDr) is calculated as a percent of the total foraminiferal count  
150 to elucidate the likelihood that foraminifera are allochthonous.

151 Three samples for accelerator mass spectrometer (AMS) radiocarbon analysis were selected  
152 using detailed bio-lithostratigraphic data derived from the sedimentological and micropaleontological  
153 investigations outlined above. Sediment units interpreted as ice-proximal during deglaciation on the  
154 basis of lithofacies, physical properties and foraminiferal assemblage data were specifically targeted  
155 to reveal depositional age constraints and establish a nascent retreat pattern across the Irish  
156 continental shelf. The three calcareous samples were obtained from 1 cm thick slab samples and  
157 comprise cold water coral fragments (*Lophelia pertusa*) and paired and single bivalve shells.  
158 Radiocarbon results are presented as both conventional ( $^{14}\text{C}$  BP) and corrected (Cal BP) ages (Table  
159 4). Radiocarbon ages were calibrated using Calib© 7.0.2 software using the global ocean average  $\Delta r$   
160 marine reservoir correction of 400 years because a regional marine reservoir effect is unavailable  
161 (Stuiver and Reimer, 1993).

## 162 **3. Results**

### 163 ***3.1. Geomorphology***

164 A series of sinuous, approximately E-W trending ridges occupy the northern Porcupine Bank  
165 and Slyne Trough (Figs. 1b, 2). The ridges range from ~5 to >65 km long and are predominantly  
166 concentrated on the Porcupine Bank, with some extending continuously into the Slyne Trough (Fig.  
167 2a, b). The two largest ridges are located in the Slyne Trough and reach heights of >30 m. The ridges  
168 are asymmetric in profile, with gentle southern and steep northern slopes (Fig. 2a, c). A broad (>5 km  
169 wide and at least 25 km long) ridge extends across the east of the study area and has a distinct NNE-  
170 SSW orientation (Fig. 2a, b). A series of high-relief (up to 15 m amplitude) corrugations oriented  
171 obliquely to the overall azimuth of the ridge occur along its crest. The southeastern corner of the  
172 study area is characterised by a gradually sloping ( $7.93^\circ$ ), relatively smooth area of seafloor. The  
173 southwestern corner of the study area is characterised by a low-relief, crenulated texture with no  
174 ridges or furrows, interpreted to be Porcupine Bank bedrock (cf. Mazzini et al., 2012).

175 The bathymetry also reveals long, meandering furrows that tend to cluster on the southern  
176 slopes of the ridges and in the Slyne Trough (Fig. 2a). The seafloor furrows are irregular and cross-  
177 cutting in pattern with a typical N-S orientation. They increase in size and occurrence toward the  
178 south of the study area and within the Slyne Trough where they reach depths of >10 m and are  
179 typically bordered laterally by berms (Fig. 2c). The depth of the furrows generally increases with  
180 bathymetric shallowing and often the furrows terminate on the southern slopes of the ridges in the  
181 study area (Fig. 2a).

## 182 **3.2. Sedimentology**

183 Seven lithofacies (Table 2) are identified based on core lithology, sedimentary structures and  
184 physical property measurements. These sedimentary properties are summarised in Table 2 and some  
185 of the x-radiograph facies are exemplified in Fig. 3. Three lithofacies associations are identified:  
186 lithofacies association 1 (LFA 1) is diamicton, occurs at the bottom of all four cores and consists of  
187 Dmm, Dmm<sub>c</sub> lithofacies (Table 2; Figs. 4, 5, 6, 7); lithofacies association 2 (LFA 2) consists of Dcm  
188 and Fl lithofacies (Table 2); the tops of all four cores are represented by lithofacies association 3  
189 (LFA 3), which consists of Sm, Sh and Suf lithofacies (Table 2; Figs. 4, 5, 6, 7).

### 190 **3.2.1. Lithofacies association 1**

191 The basal diamictons consist of Dmm lithofacies and, in cores 42 and 44, an underlying Dmm<sub>c</sub>  
192 lithofacies (Figs. 4, 5, 6, 7), is differentiated by its high consolidation (>50-120 kPa, Table 2). In core  
193 44, this Dmm<sub>c</sub> diamicton is further differentiated by its low water content (<12%, Fig. 6). The  
194 diamictons are heterogeneous in colour and grain size and contain abundant >2 cm long lonestones of  
195 variable roundness. Lonestones usually consist of black, fine-grained igneous rock, but with more  
196 variable lithologies (including granite and limestone) towards the top of the diamictons. Occasional  
197 small, highly abraded shell fragments are present in the diamictons (Figs. 4, 5, 6, 7). Cores 42 and 44  
198 consist of both Dmm and Dmm<sub>c</sub> lithofacies; in both cores the Dmm interval is at least ~1 m thick with  
199 gradational lower contacts that separate it from the underlying Dmm<sub>c</sub> lithofacies (Figs. 4, 6). The



200 diamictons of cores 42 and 43 are sandy (typical sand fractions >60%), while core 44 and 45  
201 diamictons are muddy (sand fractions <50% and as low as 30%)(Figs. 6, 7).Shear strength  
202 measurements decrease upwards from >40 kPa to <20 kPa through the diamicton in cores 42, 43 and  
203 44 (Figs. 4, 5, 6) and in cores 42 and 44 measurements up to 61 kPa and 123 kPa, respectively, have  
204 been recorded near the bottom of the Dmm<sub>c</sub> lithofacies (Figs. 4, 6). The water content,wet bulk  
205 densities and P-wave velocities of these basal diamictons are typically highly variable (Figs. 4, 5, 6,  
206 7); however, especially in core 44, the water content steadily decreases down core and reaches values  
207 as low as 11.5%. The diamicton of core 42 yields markedly lower magnetic susceptibility  
208 measurements (smoothed average measurement of 27.95 SI units x 10<sup>-5</sup>; Fig. 4) than those of core 45  
209 (smoothed average measurement of 150.23 SI units x 10<sup>-5</sup>; Fig. 7).

### 210 3.2.2. *Lithofacies association 2*

211 In each core except core 43, a massive, clast-supported, ~15 cm thick Dcm diamicton with a  
212 gradational lower contact overlies the LFA 1 diamictons (Figs. 3, 6, 7). A clast supported framework  
213 is clearly identifiable in x-radiographs (Fig. 2c) and the occurrence and amount of clast contact  
214 increases upwards through the lithofacies (i.e., the amount of matrix decreases upwards); however,  
215 there is no discernible clast orientation or sorting by size. Similar to the underlying diamictons, the  
216 Dcm diamictons are heterogeneous in colour and grain size and contain abundant large (>2 cm) clasts;  
217 although, unlike lower in the cores, the Dcm clasts are composed of variable lithologies. In core 45 a  
218 ~2.5 cm long clast found 62 cm bsf (Fig. 7) exhibits distinct striations, a rounded nose and a “plucked  
219 lee” (i.e., the clast is “bullet shaped”). Sediment physical properties are also highly variable. The  
220 Dcm lithofacies contain abundant shell fragments and in core 45 the lower contact is characterised by  
221 sandy irregularities that extend sub-vertically to vertically into the underlying Dmm. The Dcm  
222 lithofacies also infrequently incorporate deformed, randomly oriented, soft-sediment clasts (Fig. 7).  
223 In core 45, the Dcm contains a soft sediment clast composed of greyish brown (2.5Y 5/2) massive  
224 mud (Fig. 7).

225 In core 43 LFA 1 is overlain by horizontally bedded sand (Sh, LFA 3) and interbedded with  
 226 horizontally laminated silt and clay (Fl) (Fig. 5). The Fl lithofacies is ~5 cm thick and consists of  
 227 normally graded laminations ~0.5 cm thick. The Fl interval has a sharp lower contact with the  
 228 underlying Dmm diamicton. Laminae fine upwards from silty fine sand to clayey silt and have sharp  
 229 lower contacts.

230 Table 2: Lithofacies summary. Codes modified from Miall (1978) and Eyles et al. (1983).

Code	Lithofacies	Description	Interpretation and [references]*
Fl	Laminated sandy silt and clay (LFA 2)	Planar, parallel laminae, ~0.5 cm thick, normally graded, with sharp lower contacts. No identified biogenic material.	Suspension settling from meltwater plumes or fine-grained turbidites; alternatively, soft sediment rip-up clasts. [1], [2], [3], [4]
Sm	Massive sand (LFA 3)	Massive, fine-to-coarse, poorly sorted sand with shell fragments; <15 cm thick; light yellowish brown (2.5Y 6/4); sharp, conformable lower contact. Coincident with apparent coring deformation.	Outer-shelf bottom-current sediment likely deformed by coring. [5], [6], [7]
Sh	Horizontally-bedded sand (LFA 3)	Poorly developed, planar, parallel beds <2 cm thick; units are 20-35 cm thick and occasionally fine upwards; typically olive (5Y 5/3); sharp or gradational lower contact. Abundant shell fragments. High water content (up to 26%). P-wave velocity from 1,000-1,800 m/s.	Outer-shelf bottom-current sediment. [5], [6], [7]
Suf	Upward-finning sand (normally graded) (LFA 3)	Massive, <40 cm thick beds of poorly sorted sand; high concentration of shell fragments, and some granules, especially low; variable colour (2.5Y 5/2 and 6/3); sharp, conformable lower contacts. Magnetic susceptibility varies from 50-200 SI units x 10 <sup>-5</sup> from west to east.	Outer-shelf bottom-current sediment with variable terrigenous sediment content that has been winnowed of fines. Likely records seafloor transgression. [5], [6], [7], [8], [9], [10], [11]
Dcm	Clast-supported, massive diamicton (LFA 2)	Massive, 15-20 cm thick beds of clast-supported diamicton in a sandy matrix; randomly-oriented soft-sediment clasts; shell fragments and bioturbation present; gradational lower contact. Low shear stress (<20 kPa), highest magnetic susceptibility measurements in study (up to 398 SI units x 10 <sup>-5</sup> ) and highly variable P-wave and wet bulk $\rho$ measurements.	Glaciomarine diamicton from suspension settling with IRD and/or ice-shelf rain out. High clast concentration records increased dropstone production or winnowing of fines. Possibly reworked by iceberg turbation. [4], [12], [13], [14], [15], [16]
Dmm	Loose (<50 kPa), massive diamicton (LFA 1)	Massive, 90->200 cm thick units of unconsolidated muddy diamicton; randomly-oriented soft-sediment clasts; abundant limestones of various lithology high in core and similar lithology low; typically greyish brown (2.5Y 5/2); gradational lower contacts. Rare, small shell fragments; rare bioturbation at top. Variable P-wave and wet bulk $\rho$ measurements.	Glaciomarine diamicton from suspension settling, IRD and/or ice-shelf rain out with areas of iceberg turbation. [12], [13], [14], [16], [17], [18]
Dmm <sub>c</sub>	Compact (>50 kPa), massive diamicton	Massive, at least 25-80 cm thick consolidated diamicton; abundant limestones of similar lithology; variable colour (2.5Y 5/2 and 6/2); stratigraphically low with unknown lower contacts. Very rare small	Till, possibly resulting from short-lived ice shelf recoupling events that reworked and compressed existing glaciomarine sediment. Progressive

(LFA 1)	shell fragments. Low water content (typically <14%). Variable P-wave velocities and wet bulk $\rho$ up to 2.4 g/cm <sup>3</sup> ; shear stress measurements up to 123 kPa.	upwards decrease in shear strength indicates a reduction in compressive vertical pressure through time. [16], [17], [19], [20], [21]
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231 \* References: [1] Powell, 1983; [2] Hein and Syvitski 1992; [3] Ó Cofaigh and Dowdeswell, 2001; [4] Hillenbrand et al.,  
232 2013; [5] Bishop and Jones, 1979; [6] Fyfe et al., 1993; [7] Viana et al. 1998; [8] Robinson et al., 1995; [9] Saito et al., 1998;  
233 [10] Amorosi et al., 1999; [11] Barrie and Conway, 2002; [12] Kilfeather et al., 2011; [13] Anderson et al., 1983; [14] Eyles,  
234 1988; [15] Vorren et al., 1983; [16] Hillenbrand et al., 2010; [17] Evans and Pudsey, 2002; [18] Smith et al., 2011; [19]  
235 Anderson, 1999; [20] Hillenbrand et al., 2005; [21] Ó Cofaigh et al., 2005.

### 236 3.2.3. Lithofacies association 3

237 The top of each core is composed of a sand interval that contains abundant shell fragments,  
238 which typically decrease in size and occurrence upwards (Figs. 4, 5, 6, 7). The sand intervals vary in  
239 structure and are categorised as Sm, Sh and Suf lithofacies (Table 2). The sand lithofacies have sharp,  
240 apparently conformable lower contacts with the underlying lithofacies and vary in thickness from 28  
241 cm in core 43 to 50 cm in core 45. The Suf lithofacies fine upwards from poorly-sorted coarse and  
242 medium sand with granules to poorly-sorted medium sand and occur in cores 44 and 45 below Sh and  
243 Sm lithofacies with gradational lower contacts (Figs. 6 and 7). Typically, the top 5-10 cm of the sand  
244 lithofacies are deformed by the coring process.

### 245 3.3. Micropaleontology

246 Foraminifera are present in each lithofacies and analyses of all cores revealed 42 benthic taxa  
247 (Appendix 1, Tables A2, A3). Benthic foraminiferal diversity indices and general foraminiferal  
248 statistics are displayed in Appendix 1 (Table A1) and Figure 8. A maximum species richness of 24  
249 species is counted in cores 44 and 45 at 46 cm bsf and 94 cm bsf, respectively, while the lowest count  
250 of 12 species is obtained from core 43 at 85 cm bsf. Benthic foraminiferal diversity, revealed by  
251 dominance and Fisher's  $\alpha$  values, is highest in cores 44 and 45; in these two cores, Fisher's  $\alpha$  values  
252 reach >0.6 and dominance values are consistently <0.2 (Fig. 8). In cores 42 and 43, diversity  
253 generally increases upwards, evidenced by dominance values that decrease upwards from >0.3 to <0.2  
254 in both cores (Fig. 8). In all cores except core 42, foraminiferal density decreases down core from  
255 >10 to <5 tests/mg; in core 42 density is highly variable, ranging from 0.44-14.84 tests/mg with a  
256 peak at 139 cm bsf (Fig. 8).

257 Lithofacies association 1 generally coincides with high foraminiferal dominance (up to 0.38 in  
 258 cores 42 and 43) and SDr (typically >15%) values (Fig. 8, Table 3). In cores 43, 44 and 45, LFA 1 is  
 259 marked by low foraminiferal density (typically >5 tests/mg, Fig. 8). The top of LFA 1 and LFA 2  
 260 typically display a relatively abrupt increase in PTr that ranges up to 74% in core 43 (Fig. 8; Table 3).  
 261 Lithofacies association 2 displays highly variable benthic foraminiferal diversity indices (Fisher's  $\alpha$   
 262 values from 5.2-4.8 and density from 4.2-7.3; Fig. 8; Table 3). Lithofacies association 3 typically  
 263 yields low values for dominance (<0.2) and SDr (as low as 8.7% in core 44), with high values  
 264 (typically >10 tests/mg) for foraminiferal density (Fig. 8; Table 3).

265 Table 3: Lithofacies association correlations to summarised micropaleontological data.

Lithofacies association	Foraminiferal statistics	Dominant or characteristic foraminifera
1	High dominance; high SDr; low density	<i>Elphidium clavatum</i> ; <i>Cassidulina reniforme</i>
2	High PTr; variable benthic foraminifera diversity indices	<i>Discanomalina coronata</i> ; <i>Trifarina angulosa</i>
3	Low dominance; low SDr; high density	<i>Cassidulina laevigata</i> ; <i>Uvigerina mediterranea</i> ; <i>Bulimina marginata</i>

266 *Cibicides lobatulus* (Walker and Jacob, 1798) is dominant throughout the majority of the cores  
 267 and common in every lithofacies (Appendix 1, Tables A2, A3). *C. lobatulus* thrives in sandy, high-  
 268 current environments that experience sediment winnowing (Gooday and Hughes, 2002; Schönfeld,  
 269 2002). Despite its dominance in the population, the ubiquity of this species throughout the sediment  
 270 record renders it of little use as a palaeoenvironmental proxy for this study.

271 Two foraminifer species associated with glacial conditions in modern oceans have been  
 272 identified: *Elphidium excavatum* forma *clavatum* (Feyling-Hanssen, 1972) and *Cassidulina reniforme*  
 273 (Nørvang, 1945). Both species are present throughout LFA 1, however the relative abundance of both  
 274 species peaks near the top of the Dmm lithofacies (Fig. 9). The highly opportunistic species  
 275 *E. clavatum* reaches relative abundances of up to 5% near the bottom of cores 44 and 45 within LFA 1  
 276 and is generally absent towards the core tops (Fig. 9). *E. clavatum* adopts both epifaunal and infaunal  
 277 strategies to thrive near ice-marine interfaces with high sedimentation rates, variable salinity, average

278 water temperatures <1°C, and often with sea ice cover (Mudie et al., 1984; Murray, 1991; Hald et al.,  
279 1993, 1994; Linke and Lutze, 1993; Hald and Korsun, 1997; Polyak et al., 2002; Stalder et al., 2014).  
280 The infaunal species *C. reniformis* also abundant in LFA 1 (Fig. 9) and is well documented in ice-  
281 proximal marine environments in the northeastern Atlantic (Sejrup and Guilbault, 1980; Hald and  
282 Korsun, 1997; Sejrup et al., 2004). These species are typically well preserved in LFA 1, displaying  
283 less breakage and abrasion than many of the accompanying foraminifer species.

284 In most cores, the relative abundances of *Discanomalina coronata* (Parker and Jones, 1865)  
285 increase just below the lower contact of LFA 2 (Fig. 9). *D. coronata* is common in areas with high  
286 bottom currents and coarse sediment or bedrock (Hald and Vorren, 1987; Schönfeld, 1997) and is  
287 reported to thrive in areas of dead coral fragments (Morigi et al., 2012; Smeulders et al., 2014). *D.*  
288 *coronata* is associated with areas of bedrock that are distal to coral mounds on the modern Porcupine  
289 Bank (Smeulders et al., 2014). The infaunal foraminifer species *Trifarina angulosa* (Williamson,  
290 1858) is abundant throughout the examined cores and has been documented as a common species on  
291 the Porcupine Bank (Weston, 1985; Smeulders et al., 2014) and in Atlantic polar front regions  
292 (Mackensen et al., 1993). *T. angulosa* is reported to thrive in areas of coarse sediment and high  
293 bottom currents (Mackensen et al., 1993; Klitgaard Kristensen and Serjup, 1996) and in cores 42 and  
294 43 its relative abundances undergo rapid changes near the lower contact of LFA 2 (Fig. 9). *Cibicides*  
295 *refulgens* (de Montfort, 1808) is also common near LFA 2 and is associated with high bottom currents  
296 and areas of sediment winnowing (Gooday and Hughes, 2002; Smeulders et al., 2014).

297 The dominant foraminifer species in LFA 3 are the epifaunal *Cassidulina laevigata* (d'Orbigny,  
298 1826, 1847) and infaunal species *Uvigerina mediterranea* (Hofker, 1930) (Fig. 9). Both species are  
299 associated locally with sheltered areas, preferentially on or near cold-water coral mounds (Smeulders  
300 et al., 2014). *Bulimina marginata* (d'Orbigny, 1826) is common near the core tops and is also  
301 associated with modern living and dead coral mounds on the Porcupine Bank (Morigi et al., 2012;  
302 Smeulders et al., 2014) as well as phytodetrital sediment in the Rockall Trough (Gooday and Hughes,  
303 2002).

### 304 3.4. Chronology

305 AMS radiocarbon dating was conducted on three samples consisting of bivalve shells and cold-  
306 water coral (*Lophelia pertusa*) fragments; results are summarised in Table 4. The radiocarbon ages  
307 are within marine isotope stage (MIS) 2. The oldest radiocarbon age recovered in this study is ~25  
308 Cal. kaBP. This age is derived from a *Lophelia pertusa* fragment collected 180 cm bsf in core 44,  
309 encased in a Dmm<sub>c</sub> diamicton (Fig. 6). *Lophelia pertusa* is known to colonise the modern seafloor  
310 near the study area (Scoffin and Bowes, 1988; Heindel et al., 2010; Smeulders et al., 2014) and thus is  
311 considered a viable source of locally bio-mineralised radiocarbon-datable material. The youngest age  
312 of ~19ka Cal. BP is from a paired, unabraded and unbroken bivalve shell; this sample was collected  
313 from Suf sand (the only age derived from a non-diamictic lithofacies) 36 cm bsf in core 42 (Fig. 4;  
314 Table 4). A single (unpaired), unbroken and unabraded bivalve shell sampled from Dmm diamicton  
315 94 cm bsf in core 45 yielded an age of ~20 ka Cal. BP (Table 4). All specimens sampled for  
316 radiocarbon dating were largely free of obvious surface wear and are deemed to have been  
317 incorporated into the surrounding sediment close to their point of origin based on the quality of their  
318 preservation.

319 Table 4: radiocarbon results.

Core	Depth (cm bsf)	Sample material	14C age (yrs. BP)	Calibrated age (yrs. BP)	δ <sup>13</sup> C (‰)	Surrounding lithofacies	Laboratory code
42	36	Paired bivalve shell	17900±89	19182±155	-4.7	Suf	Poz-66484
44	180	Coral fragment	20710±90	24720±260	-1.3	Dmm <sub>c</sub>	Beta-334419
45	94	Single bivalve shell	18733±107	20254±151	4.3	Dmm	Poz#2-66430

320

## 321 **4. Interpretation**

### 322 **4.1. Geomorphology**

#### 323 **4.1.1. Seafloor furrows**

324 Seafloor furrows are common in the study area and are concentrated in the Slyne Trough (Fig.  
325 2). Because of their irregular patterns, adjacent presence of lateral berms (Fig. 2a) and bathymetric  
326 association (amplified depth and berm formation with height), the seafloor furrows are interpreted as  
327 iceberg scours (Belderson et al., 1973; Dowdeswell et al., 1993; Ó Cofaigh et al., 2002, 2010); the  
328 common N-S orientation and tendency to deepen or end on the southern ridge slopes suggest a calving  
329 ice margin toward the south of the study area and a northward palaeocurrent direction. Thus we  
330 interpret the primary ice source to be the BIIS, which is in agreement with an ice-rafted detritus (IRD)  
331 study of deep sea cores along the western BIIS continental margin (Scourse et al., 2009).

#### 332 *4.1.2. Seafloor ridges*

333 Sinuous ridge asymmetry is typical of the ice proximal/distal discrepancy expected from glacial  
334 push moraines (Boulton, 1986). Some ridges possess southern slopes with low gradients (Fig. 2b),  
335 forming an asymmetrical profile that more closely resembles grounding-zone wedges (e.g., Bart and  
336 Cone, 2012; Dowdeswell and Fugelli, 2012; Jakobsson et al., 2012). However, the sinuosity and in  
337 places “scalloped” form of the ridges contrasts slightly with typical, arcuate end moraine structures  
338 (e.g. Bradwell et al., 2008; Ó Cofaigh et al., 2010).

339 Although the geomorphic interpretation of the individual E-W trending ridges is uncertain, the  
340 parallel to sub-parallel, ostensibly sequential organisation of the ridges across the study area, coupled  
341 with their extension across varied terrain suggest ice-marginal formation. Furthermore, the intensive  
342 iceberg scouring supports the concept of a nearby palaeo-ice margin. Thus, the landforms are  
343 tentatively interpreted as a record of westward BIIS extension across the Irish continental shelf. Due  
344 to discrepancies in scale and morphology with previously documented BIIS end moraines west of  
345 Ireland (which are arcuate and reach lengths of ~125 km; Ó Cofaigh et al., 2010; Clark et al., 2012a)  
346 an interpretation of ice-marginal deposition during relatively short-lived ice extensions with an  
347 actively calving margin is preferred. The radiocarbon ages recovered from on and near the sinuous  
348 ridges date from MIS 2, demonstrating that the landforms incorporate calcareous material that was  
349 bio-mineralised during the Midlandian Glaciation.

350 The orientation of the large, corrugated SSW-NNE trending ridge relative to the  
351 aforementioned abundant E-W trending ridges suggests a different geomorphic evolution. The  
352 corrugations are apparently a series of E-W trending ridges that are overprinted on the larger SSW-  
353 NNE trending ridge. They have a similar orientation to the neighbouring sinuous ridges and appear to  
354 be situated as eastward extensions of those ridges (Fig. 2a). Because of these characteristics, we  
355 tentatively interpret this ridge as an earlier glacial landform, likely an end moraine, which has been  
356 subsequently overprinted by the E-W trending ridges.

#### 357 ***4.2. Sedimentology and palaeoenvironment***

358 The four cores analysed for this study are interpreted to provide a record of glacial  
359 sedimentation in the Slyne Trough and on the Porcupine Bank. Two of the cores (44 and 45) are  
360 taken from near the crests of moraines in the Slyne Trough and recover 2.3-2.9 m of sediment.  
361 Because this sediment has properties characteristic of subglacial deposition and is sampled from the  
362 moraine crests, we interpret it as the ridge-forming deposit.

##### 363 ***4.2.1. Lithofacies association 1***

364 The massive structure, low water content and high (50-123 kPa) shear strength that characterise  
365 the Dmm<sub>c</sub> lithofacies are consistent with vertical compaction from an overriding glacier; the  
366 progressive up-core decrease in shear strength suggests a gradual decrease in compaction over time  
367 (Anderson, 1999; Evans et al., 2005). Furthermore, the striated, “bullet shaped” morphologic  
368 characteristics on a clast sampled from core 45 are interpreted to indicate proximal subglacial  
369 transport (Sharp, 1982). The presence of heavily fragmented shell material indicates that the  
370 diamicton incorporated earlier marine deposits and the westward decrease in magnetic susceptibility  
371 measurements denotes a reduction in terrigenous sediment supply (Robinson et al., 1995; Shevenell et  
372 al., 1996). These variables are interpreted as a record of subglacial sedimentation (till, Fig. 10). The  
373 incorporation of biogenic material and reduction of magnetic susceptibility along the geographically  
374 and geomorphologically interpreted ice flow direction (westward) suggests either a subglacial



375 sediment supply that incorporated large amounts of pre-glacial marine sediment or an ice mass that  
376 was only periodically grounded and failed to transport large amounts of terrigenous sediment to the  
377 shelf edge (cf. Ó Cofaigh et al., 2005; Garcia et al., 2011).

378 The Dmm lithofacies are characterised by abundant lonestones in a less compact (shear strength  
379 <50 kPa, often <10 kPa), mud-rich matrix that is consistent with subglacial deposition as a dilatant till  
380 (Evans et al. 2005; Ó Cofaigh et al., 2005, 2007), or glaciomarine sedimentation from suspension  
381 settling and IRD (Evans and Pudsey, 2002; Hillenbrand et al., 2005; Kilfeather et al., 2011; Smith et  
382 al., 2011). The relative paucity of observable shell fragments or bioturbation in the Dmm diamicton  
383 from cores 42 and 44 and the bottom of core 43 (Figs. 4, 5, 6), along with their variable and moderate  
384 shear strengths (8-42 kPa) suggests that these diamictons are a dilatant till deposited over a highly  
385 compact till unit by a deforming, overriding ice mass (e.g. Smith, 1997; Vaughan et al., 2003; Ó  
386 Cofaigh et al., 2005). Conversely, the low shear strength (<15 kPa), relatively abundant shell  
387 fragments, appearance of till pellets and bioturbation within the Dmm diamicton of core 45 and at the  
388 top of LFA 1 in core 43 (Figs. 5, 7) suggest that the diamicton was deposited by proglacial or sub-ice  
389 shelf rainout (e.g., Evans and Pudsey, 2002; Hillenbrand et al., 2005; Kilfeather et al., 2011; Smith et  
390 al., 2011). The stratigraphic position of the proglacial suspension sediment above the dilatant till in  
391 core 43 indicates that the suspension settling occurred during BIIS retreat from the Porcupine Bank.

392 Lonestones within the sub-ice shelf or proglacial Dmm diamicton are interpreted as IRD based  
393 on their random orientations and variable sizes (e.g., Grobe, 1987; Heinrich, 1988). Their abundance  
394 suggests intense iceberg activity or periods of sub-ice shelf sedimentation (Evans and Pudsey, 2002).  
395 A sub-ice shelf interpretation is supported by the lithologic similarity of the dropstones at the base of  
396 the Dmm diamicton, which tends to be variable in open-water environments (Pudsey and Evans,  
397 2001; Domack et al., 2005). Thus, the Dmm diamicton in core 45 and at the top of LFA 1 in core 43  
398 is interpreted as *in situ* sub-ice shelf or ice-proximal iceberg rain-out sediment (Fig. 10).

399 High foraminiferal dominance values and the commonly low foraminiferal density in LFA 1  
400 (Table 3) suggest poor palaeoproductivity. The typically low PTr values of LFA 1 may indicate a  
401 reduction in surface productivity (Diester-Haass, 1978; Ovsepyan et al., 2013), although this metric  
402 may also reflect changes in sea level and rates of carbonate dissolution (Berger and Diester-Haass,  
403 1988). An anomalously low PTr value of 21.5% is recorded in core 42 at 78 cm bsf (Fig. 8), which  
404 correlates with the highest SDr value (35.8%) recorded in this study; this suggests that the low PTr  
405 value may record the preferential breaking of fragile planktonic tests during sediment reworking or  
406 sample processing rather than actual palaeoenvironmental conditions. The occurrence of well-  
407 preserved *E. clavatum* and *C. reniforme* near the top of LFA 1 suggests a palaeoenvironment that  
408 experienced high sedimentation rates, variable salinity and average water temperatures  $<1^{\circ}\text{C}$  (Murray,  
409 1991; Hald et al., 1993, 1994; Linke and Lutze, 1993; Hald and Korsun, 1997; Sejrup et al., 2004).  
410 The Dmm<sub>c</sub> lithofacies at the bottom of core 44 is associated with a high SDr value ( $>25\%$ ; Fig. 9),  
411 which suggests an increased amount of subglacial and ice-proximal transport in this sediment (Melis  
412 and Salvi, 2009). Because of its sedimentological and micropaleontological characteristics, LFA 1 is  
413 interpreted to indicate glacial conditions that likely experienced ice-proximal meltwater influx, cold  
414 temperatures and periods of overriding by the BIIS that resulted in sediment compaction (Dmm<sub>c</sub>) and  
415 the incorporation of allochthonous foraminifer species.

416 Two AMS radiocarbon dates are derived from samples taken from LFA 1 between 75 and 180  
417 cm bsf (Fig. 10; Table 4). These dates range from  $24,720 \pm 260$  to  $20,254 \pm 151$  Cal. BP, confirming a  
418 Midlandian depositional age. The ages are from cores 44 (180 cm bsf) and 45 (94 cm bsf) and  
419 constrain the deposition of the Dmm<sub>c</sub> and overlying Dmm lithofacies, respectively (Fig. 10; Table 4).  
420 In core 44 the date from 180 cm bsf provides a maximum age for the diamicton and indicates that its  
421 deposition occurred after  $24,720 \pm 260$  Cal. BP (Fig. 10). In core 45 the sample from 94 cm bsf also  
422 provides a maximum age for the Dmm diamicton and indicates that it was deposited after  $20,254 \pm 151$   
423 Cal. BP (Fig. 10).

#### 424 4.2.2. Lithofacies association 2

425 The similarities in clast size, roundness and lithology between the Dcm lithofacies and the top  
426 of the underlying LFA 1 diamictons suggest a similar primary sediment source. Thus the increase in  
427 clast contact in LFA 2 is interpreted as the result of either fine sediment winnowing (Eyles, 1988) or a  
428 period of increased IRD production (Kilfeather et al., 2011). Fine sediment winnowing may result  
429 from increased palaeocurrents. Given the geomorphically interpreted, northward palaeocurrent  
430 direction through the Slyne Trough, it is plausible that palaeocurrents may have been hindered by ice  
431 occupation and, thus, ice loss would have resulted in an abrupt palaeocurrent increase. An increase in  
432 IRD production may also result from ice shelf break up (Kilfeather et al., 2011). Soft-sediment clast  
433 inclusions have similar sedimentary properties to the underlying diamicton and are interpreted as rip-  
434 up clasts that were likely dislodged during iceberg turbation (Hillenbrand et al., 2013) or till pellets  
435 from iceberg rainout (Ovenshine, 1970). The IRD lithological variability indicates a multitude of  
436 sediment provinces, which suggests the establishment of an open-water environment and deposition  
437 from icebergs (Domack et al., 2005). The vertical, sandy irregularities that bisect the lower contact of  
438 the Dcm diamicton in core 45 are interpreted as infilled burrows (bioturbation, Fig. 7); this and the  
439 increased occurrence and size of shell fragments support an interpretation of deposition during ice  
440 shelf break up leading to an open water environment and an increasingly distal ice margin (Smith et  
441 al., 2011).

442 Based on its planar, parallel structure and silty fine sand to clayey silt texture, the Fl lithofacies  
443 may be interpreted as ice-distal suspension sediment or a fine-grained turbidite. Its position within  
444 the IRD-rich glaciomarine diamicton (Dmm) and its discrete occurrence in the core suggest that it is  
445 most likely a turbidite that originated on the nearby 1.4° slope of the Porcupine Bank or the flanks of  
446 sediment ridges (Fig. 2). This interpretation is supported by previous studies that document  
447 subaqueous fine-grained turbidite formation on similar gradient slopes (e.g., Schwab et al., 1996).  
448 Alternatively, the Fl lithofacies may be a large soft-sediment clast that happens be oriented with its  
449 laminae horizontal and spans the 11 cm width of the core. If this interpretation is correct, the Dmm  
450 lithofacies in core 43 is relatively rich in rip-up clasts (cf. Hillenbrand et al., 2013) and their similarity  
451 to the underlying Dmm diamicton suggests that they are plucked from overridden glaciomarine

452 deposits and subsequently deposited below a floating ice mass as till pellets (Domack et al. 1999;  
453 Evans et al. 2005; O Cofaigh et al. 2005). Either interpretation is compatible with sedimentation  
454 during transition from ice-proximal glacial conditions to the establishment of open-water conditions  
455 following an eastward retreating ice margin.

456         The abrupt increase in PTR values in LFA 2 indicates an increase in surface productivity  
457 (Diester-Haass, 1978; Ovsepyan et al., 2013), which supports an interpretation of ice break up and  
458 retreat. Lithofacies association 2 also marks the transition to a palaeoenvironment dominated by  
459 foraminifer species associated with modern, high-current conditions on the Porcupine Bank. The  
460 increase in *D. coronata* relative abundance just below the lower contact of LFA 2 suggests an increase  
461 in palaeocurrent velocities (Hald and Vorren, 1987; Schönfeld, 1997). Increases in the relative  
462 abundance of *C. refulgens* also indicates energetic palaeocurrents and sediment winnowing (Gooday  
463 and Hughes, 2002; Smeulders et al., 2014). Rapid, although occasionally opposing, fluctuations in  
464 the relative abundance of *T. angulosa* suggest a period of palaeoenvironmental transition. Because of  
465 these foraminiferal characteristics this group is considered indicative of a transition to unsheltered  
466 habitats that experience high currents and receive a relatively high food supply.

467         Based on its sedimentological and micropaleontological characteristics, LFA 2 is interpreted to  
468 record a transitional period between the underlying ice-proximal and subglacial sediment and the  
469 overlying sandy deposits of LFA 3. This transitional period likely experienced an increase in  
470 palaeocurrent activity that coincided with an increased rate of IRD sedimentation. These conditions  
471 likely resulted from an increase in the geomorphically-revealed northward palaeocurrent due to the  
472 loss of an ice mass over or grounded to the Slyne Trough. Additionally, ice shelf break up in the area  
473 could also account for an increase in IRD production. These conditions are interpreted to mark the  
474 initiation of BIIS retreat and the establishment of open ocean conditions in the area. The age of these  
475 lithofacies is constrained by AMS radiocarbon dates derived from underlying and overlying strata to  
476 between  $20,254 \pm 151$  and  $19,182 \pm 155$  Cal. BP (Fig. 10).

477 4.2.3. Lithofacies association 3

478 Based on lithology, structure, biogenic content, stratigraphic position and geographic position  
479 on the shelf, LFA 3 is interpreted as postglacially-reworked glacial material (cf. Fyfe et al., 1993).  
480 A glacially-influenced, primary depositional environment is supported by the higher magnetic  
481 susceptibility measurements in core 45 (smoothed average SI units  $\times 10^{-5}$  of 150.23, Fig. 7) relative to  
482 the westernmost core 42 (smoothed average SI units  $\times 10^{-5}$  of 27.95, Fig. 4), which may indicate  
483 higher terrigenous sediment supplies to the east (Robinson et al., 1995; Shevenell et al., 1996). The  
484 sands were likely reworked by strong, but gradually weakening (suggested by Suf lithofacies), bottom  
485 currents (Bishop and Jones, 1979; Fyfe et al., 1993; Viana et al. 1998). This interpretation is further  
486 supported by winnowing in the underlying LFA 2 and previous micropaleontological (Smeulders et  
487 al., 2014) and sedimentological (De Haas et al., 2009) studies on the Porcupine Bank and flanks of the  
488 nearby Rockall Trough. This gradual palaeocurrent weakening is interpreted as a signature of sea level  
489 transgression on the Irish continental shelf and shares similar sedimentary characteristics with other  
490 postglacial transgressive marine sediment deposits and stratigraphic sequences (Saito et al., 1998;  
491 Amorosi et al., 1999; Barrie and Conway, 2002).

492 The low foraminiferal dominance values in LFA 3 (Fig. 8; Table 3), indicate high surface  
493 palaeoproductivity (Diester-Haass, 1978; Ovsepyan et al., 2013). The typically high foraminiferal  
494 density values also indicate increased palaeoproductivity, likely from decreasing glacial influence  
495 (Hebbeln and Wefer, 1991; Carmack and Wassmann, 2006). The increasing relative abundance of *C.*  
496 *laevigata*, *U. mediterranea* and *B. marginata* in LFA 3 suggests an increased food supply and the  
497 emergence of a palaeoenvironment resembling modern “on-mound” (i.e. on cold water coral mounds)  
498 environments on the Porcupine Bank (Smeulders et al., 2014). Thus, based on its sedimentological  
499 and micropaleontological attributes, LFA 3 is interpreted as outer-shelf bottom-current sediment with  
500 variable terrigenous sediment content that has been winnowed of fines; the normal grading of the Suf  
501 lithofacies records sea level transgression (Bishop and Jones, 1979; Fyfe et al., 1993; Viana et al.  
502 1998).

503 The age of LFA 3 is constrained by an AMS radiocarbon age derived from 36 cm bsf in core 42  
504 to likely be younger than  $19182\pm155$  Cal. BP (Fig. 10; Table 5). Because this age is calculated from  
505 the westernmost (likely most ice-distal) core, it is interpreted to most accurately represent the earliest  
506 phase of post-glacial sedimentation in the study area. This record of transgression is slightly earlier  
507 than some terrestrial (shoreline) data indicators (e.g., Kuchar et al., 2012), which is likely the result of  
508 an earlier onset of deglaciation and a diminished glacio-isostatic effect on the outer shelf.

## 509 **5. Discussion**

### 510 ***5.1. The late Midlandian BIIS on the Porcupine Bank***

#### 511 *5.1.1. Signature of BIIS position*

512 The seafloor morphology of the study area is dominated by long, sinuous ridges seemingly  
513 deposited sequentially across the northern flank of the Porcupine Bank and the Slyne Trough (Figs. 2,  
514 11a). These ridges are largely composed of glaciomarine diamicton (LFA 1) that tends to be compact  
515 (>50 kPa) and low in water content towards the core bottoms, suggesting periods of BIIS overriding  
516 and compression (Anderson, 1999; Evans et al., 2005). Homogeneous clast lithology and structure in  
517 the lower diamicton (Dmm<sub>c</sub> and upper Dmm) suggests a subglacial or sub-ice shelf origin (Pudsey  
518 and Evans, 2001; Domack et al., 2005). Changes in LFA 1 magnetic susceptibility (Figs. 4, 7) and  
519 grain size (sand-sized particles 30% by weight in core 45 Dmm and 69% in core 43 Dmm) across the  
520 study areas suggest that the BIIS overrode and remobilised pre-glacial material as till (cf. Evans and Ó  
521 Cofaigh, 2003; Ó Cofaigh et al., 2011). The abundance of foraminiferal tests (up to 1.3-1.4 benthic  
522 individuals/mg in core 44, Appendix 1, Table A3) with signs of remobilisation (SDr up to 25% in core  
523 44, Fig. 8) and the presence of both cold and warm water taxa in the Dmm<sub>c</sub> lithofacies supports an  
524 interpretation of glacitected pro- and pre-glacial marine material (Hald et al., 1990; Melis and  
525 Salvi, 2009). Thus, the ridges are interpreted as a combination of BIIS end moraines, grounding-zone  
526 wedges, or possibly push ridges from ice shelf recoupling (Fig. 11). An interpretation of ridge  
527 formation from temporary ice shelf recoupling is compatible with sedimentary and

528 micropaleontological evidence of ice shelf formation. Furthermore, the sequential ridge formation is  
529 concentrated on bathymetric highs on the Porcupine Bank and Slyne Trough, suggesting formation  
530 along a floating ice mass during periods of grounding (Fig. 2).

531 The large, corrugated ridge in the east of the study area is geomorphically and, presumably,  
532 genetically distinct from the abundant sinuous ridges. Individual corrugations appear to be oriented  
533 with the smaller moraines on the Porcupine Bank and Slyne Trough (i.e. as extensions thereof) and  
534 have a similar scale (Fig. 2). This suggests that the corrugated ridge is overprinted by the smaller,  
535 sinuous ridges and is therefore older. Based on its differing orientation, larger scale, and apparent  
536 older age, we hypothesise that this large ridge is a BIIS terminal moraine (or grounding-zone wedge)  
537 deposited in front of an ice lobe that was grounded to the continental shelf. In the absence of any  
538 chronological control, it is unknown if this landform dates to the Midlandian or an earlier glaciation.

#### 539 *5.1.2. Ice shelf formation and break up*

540 The Dmm diamicton in core 45 and overlying the dilatant till at the base of core 43 is  
541 interpreted to record a period of post-grounded ice advance, sub-ice shelf sedimentation based on its  
542 loose consolidation (typically <15 kPa), abundant dropstones, incorporation of till pellets, and  
543 upwards increase in biogenic activity (bioturbation and shell fragments) (cf. Hillenbrand et al., 2010;  
544 Kilfeather et al., 2011). The presence of till pellets and abundant dropstones oriented randomly  
545 within a matrix of fine-grained sand and mud is consistent with sedimentation from rain out from  
546 icebergs or ice shelves (Evans and Pudsey, 2002; Hillenbrand et al., 2005; Kilfeather et al., 2011;  
547 Smith et al., 2011). Clast lithologic homogeneity is similar between the lower glaciomarine sediment  
548 and the underlying till, suggesting a sub-ice shelf depositional environment (Pudsey and Evans, 2001;  
549 Domack et al., 2005; Kilfeather et al., 2011) or a proximal ice source. The formation of an ice shelf is  
550 supported by the common, upwards increases in planktonic foraminifera and overall foraminiferal  
551 densities in the Dmm diamicton (Fig. 8) because these increases suggest an increase in  
552 palaeoproductivity (Hebbeln and Wefer, 1991; Carmack and Wassmann, 2006), which may have  
553 resulted from the introduction of relatively warm Atlantic water influx (cf. Kilfeather et al., 2011; Fig.

554 11). The successive, sinuous ridges along the Porcupine Bank and Slyne Trough are also compatible  
555 with the development of an ice shelf following the advance of grounded ice across the shelf to the  
556 Porcupine Bank. This ice shelf likely developed over the Slyne Trough, with the Porcupine Bank  
557 acting as a pinning point (e.g. Joughin et al., 2004) during initial uncoupling (Fig. 11).

558 An upwards increase in lithological heterogeneity through the glaciomarine (Dmm) diamicton  
559 suggests the emergence of a period of IRD deposition from ice with multiple source areas (Pudsey  
560 and Evans, 2001; Domack et al., 2005). We interpret this as the signature of initial ice shelf break up  
561 that lead to the eventual establishment of open water conditions (cf. Kilfeather et al., 2011). A period  
562 of either increased palaeocurrent activity that enabled winnowing, or increased coarse sediment  
563 supply, or a combination of both followed the ice break up, evidenced by the Dcm lithofacies that  
564 overlies the glacial diamicton (Fig. 11).

565 The numerous iceberg scours in the study area appear preferentially aligned with the Slyne  
566 Trough and indicate a roughly N-S oriented palaeocurrent following the ice shelf break (Figs. 2a,  
567 11d). Further qualitative geomorphic evidence for an approximately northward palaeocurrent is  
568 provided by a common northward deepening of scours against the rising floor of the Slyne Trough  
569 and scours that terminate on the southern flanks of ridges (Figs. 2a, 11d). If this palaeocurrent  
570 interpretation is correct, the extension of the ice sheet over the Slyne Trough may have sufficiently  
571 disrupted local palaeocurrents through the Slyne Trough to allow the deposition of silt and clay seen in  
572 the underlying Dmm<sub>c</sub> and Dmm lithofacies (Fig. 11).

## 573 **5.2. Implications for BIIS chronology**

### 574 *5.2.1. BIIS extent and chronology of advance*

575 We present multiproxy data on ice position that indicates a ~80 km extension from previous  
576 reconstructions of maximum BIIS extent west of Ireland that locate the maximum extent  
577 approximately along the Galway Lobe Moraine (Sejrup et al., 2005; Scourse et al., 2009; Clark et al.,  
578 2012a; Fig. 1a). This ice advanced as a grounded ice mass that traversed the Slyne Trough to the



579 northern Porcupine Bank (Figs. 1, 11). This extension constitutes a ~180 km advance offshore of  
580 County Mayo, Ireland at maximum extent. This places BIIS maximum extent ~100-km farther west  
581 from the shelf moraines offshore of County Donegal described by Benetti et al. (2010), Ó Cofaigh et  
582 al. (2010) and Dunlop et al. (2010) and provides supporting evidence for grounded ice extension to  
583 the shelf edge west and north of Ireland. The new extent adds a ~6,700 km<sup>2</sup> areal increase over  
584 previous BIIS estimates, summarised by Clark et al. (2012a) to be ~840,000 km<sup>2</sup>. This constitutes a  
585 ~3% increase in the estimated areal extent of the BIIS Irish Sector, previously projected to have  
586 reached ~222,500 km<sup>2</sup> (Greenwood and Clark, 2009). Sedimentary and micropaleontological  
587 evidence indicates that this ice mass likely uncoupled from the seafloor and formed an ice shelf prior  
588 to retreat (Fig. 11).

589 Three new AMS radiocarbon ages are the first to constrain the advance of the BIIS onto the  
590 western Irish continental shelf to within the last ~24,720±260 Cal. BP (Table 5; Figs. 10, 11a). The  
591 oldest date of 24,720±260 Cal. BP (Table 5) is sampled from a Dmm<sub>c</sub> diamicton interpreted to be till  
592 based on its high consolidation (>80 kPa) and low water content (<14%) (Fig. 6). This suggests an ice  
593 advance at least as far offshore as the Slyne Trough ≤24,720±260 Cal. BP; this is ≥2,000 years  
594 younger than previous estimates of BIIS extension to the western Irish shelf edge established by  
595 radiocarbon ages from IRD-rich sediment along the western Irish margin and Rosemary Bank (Peck  
596 et al., 2006; Scourse et al., 2009) and sediment supply to the Donegal-Berra Fan (Wilson et al., 2002).  
597 However, this younger advance is consistent with a scenario of continued BIIS extension beyond the  
598 previously suspected last glacial (Midlandian) maximum extent on the Irish continental shelf (Fig. 1a).  
599 Midlandian ice advance to the Slyne Trough suggests that the shelf moraines west and north of  
600 County Donegal (Benetti et al., 2010; Dunlop et al., 2010; Ó Cofaigh et al., 2010) were also likely  
601 deposited during the last glaciation. This ice sheet advance towards the Porcupine Bank  
602 likely predates formation of the large Galway Lobe Moraine on the shelf west of Ireland (Clark et al.,  
603 2012a; Fig. 1). This is consistent with the interpretation of the large corrugated ridge (Fig. 2a, b) as  
604 an earlier, potentially Midlandian, BIIS moraine and previous geomorphological models of Irish Ice  
605 Sheet behaviour (e.g., Greenwood and Clark, 2009; Clark et al., 2012a).

606 5.2.2. *Chronology of BIIS retreat*

607 The importance of establishing a complete record of BIIS retreat is outlined by Clark et al.  
608 (2012a) and improvements should logically begin with refining ice sheet chronology and maximum  
609 extent. This paper provides the geographic and chronologic starting points for retreat rate calculations  
610 for the westernmost margin of the BIIS. AnAMS radiocarbon age of  $19,182 \pm 155$  Cal. BP (Table 5)  
611 derived from postglacial lithofacies (LFA 3) that overlie the transitional glaciomarine lithofacies  
612 (LFA 2) dates the establishment of open water conditions (Fig. 11c, d). This age confines the likely  
613 duration of BIIS occupation on the outer shelf as either grounded or floating ice to a ~5,500 year  
614 window commencing ~25,000BP and with retreat underway by ~19,500 BP (Fig. 11). Ice occupation  
615 may have been prolonged by the development of an ice shelf that acted as a buttress against ice flow  
616 (Rignot et al., 2004; Alley et al., 2007; Fig. 11).

617 Given this chronologic evidence, we interpret the Galway Lobe Moraine as a recessional  
618 moraine or grounding-zone wedge. The Galway Lobe Moraine's flat-topped morphology (Clark et  
619 al., 2012a; Fig. 1b) is compatible with formation as a grounding-zone wedge (cf. Bart and Cone,  
620 2012; Dowdeswell and Fugelli, 2012; Jakobsson et al., 2012) and its large size (>20 km wide, Fig 1b)  
621 suggests that it was formed during a significant stillstand during retreat (Dowdeswell et al., 2008).  
622 This stillstand may be the product of ice flow buttressing by the ice shelf that persisted over the Slyne  
623 Trough, which is evidenced by sub-ice shelf sedimentation and paleontological indications for ice-  
624 proximal meltwater influx and cold temperatures.

625 No other age constraints are currently available across the western Irish shelf. Thus we are  
626 forced to consider terrestrial age constraints from the west of Ireland to assess implications for marine  
627 termini retreat rates. Many terrestrial ages from the west of Ireland are contested (e.g., Bowen et al.,  
628 2002; Ó Cofaigh and Evans, 2007; Clark et al., 2009, 2012a; Ballantyne, 2010) and relatively few are  
629 available from counties Galway and Mayo (Clark et al., 2012a). Most ages place initial deglaciation  
630 of the west Irish coast around ~20 kyr BP (McCabe et al., 2005; Ballantyne, 2010; Clark et al.,  
631 2012a). Thus, we agree with the assessment of Ballantyne (2010) that the best estimate for the start of

632 terrestrial deglaciation (ice free “peripheral zones”) is ~20 ka BP. This estimate suggests that  
633 retreat for the ~180 km long western BIIS marine sector occurred during a ~1,000-2,500 year time  
634 window, yielding a range of possible retreat rates from ~180 to 72 myr<sup>-1</sup>. These rates are comparable  
635 to those for BIIS retreat along the Irish Sea Lobe marine-terminating margin, estimated at 145 myr<sup>-1</sup>  
636 (Clark et al., 2012). Other comparable estimates for retreat rates are reported from Antarctic marine  
637 margins during West Antarctic Ice Sheet retreat from the outer Antarctic Continental Shelf during the  
638 last deglaciation in the Ross and Bellingshausen seas (Conway et al., 1999; Kilfeather et al., 2011).

## 639 **6. Conclusions**

- 640 • Geomorphic, sedimentary and micropaleontological data from the Porcupine Bank and Slyne  
641 Trough, west of Ireland, indicate that a series of sinuous ridges on the outer shelf are most likely  
642 moraines or grounding-zone wedges. Their presence confirms and extends the  
643 geomorphological evidence of BIIS extension across the Irish continental shelf.
- 644 • These new data extend the BIIS margin by up to ~80 km further to the west. This equates to an  
645 estimated 6,700 km<sup>2</sup> areal increase in grounded ice and a ~3% increase in the estimated areal  
646 extent of the BIIS Irish Sector.
- 647 • A radiocarbon age sampled from highly consolidated till that underlies loose dilatant till provides  
648 the first constraints on the timing of BIIS marine margin advance to after 24,720±260 Cal. BP.
- 649 • Ice shelf development and possible readvance(s) onto the Porcupine Bank likely followed  
650 uncoupling of the grounded ice sheet on the Slyne Trough. The northern Porcupine Bank  
651 probably acted as an ice shelf pinning point during uncoupling and minor readvances are recorded  
652 by glaciotectonic ridges.
- 653 • Sedimentological and micropaleontological evidence are strongly stratigraphically correlated and  
654 record ice shelf break up and the establishment of open water conditions over the Slyne Trough.

- 655 • A radiocarbon age from the draping Holocene marine sediment constrains ice shelf break up to  
656 before 19,182±155 Cal. BP, following a ≤5,500 year occupation and a retreat rate of ~180 to 72  
657 myr<sup>-1</sup> from the northern Porcupine Bank to the Slyne Trough.
- 658 • Iceberg scours indicate a roughly northward iceberg trajectory following ice shelf break up.  
659 Icebergs were concentrated in the Slyne Trough where palaeocurrents forced iceberg keels into  
660 bathymetric highs, suggesting a BIIS ice provenance.

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## 678 **Figure captions**

679 Figure 1: **(a)** Regional schematic map locating the study area (bold black rectangle) amongst BIIS extents (discussed in text)  
680 and relevant palaeoglaciological features west of Ireland. Core locations shown as white dots. “Previous westernmost BIIS  
681 extent” represents BIIS extent prior to this study and is modified from Sejrup et al. (2005), Scourse et al. (2009), Clark et al.  
682 (2012a) and Sacchetti et al. (2012); “BIIS maximum (this study)” incorporates interpretations from this study. The  
683 “Previously accepted LGM” is adapted from Bowen et al. (1986). Abbreviations: D.B. = Donegal Bay, G.B. = Galway Bay.  
684 **(b)** DEM of the study area created from an INFOMAR bathymetric raster; area coincides with the bold black rectangle in  
685 (a). Core locations are shown as labelled white dots. Arrows 1 and 2 indicate sinuous ridges and arrow 3 marks the large,  
686 corrugated N-S trending ridge. The large moraine mapped by Clark et al. (2012a) is visible and labelled (referred to here as  
687 the Galway Lobe Moraine) in the hillshaded OLEX® data west of the study area (Courtesy of Ocean DTM).

688

689 Figure 2: **(a)** INFOMAR bathymetric 25-m resolution DEM revealing seafloor morphology and core locations (white,  
690 labelled dots). Sets of sinuous, E-W trending ridges are discernible and some are highlighted with grey dashed lines. The  
691 large, corrugated, roughly N-S trending ridge is outlined with a black dashed line; individual corrugations are indicated with  
692 arrows. Seafloor furrows are visibly concentrated within the Slyne Trough and towards the south of the study area. A series  
693 of approximately N-S oriented transects (X-X', Y-Y', Z-Z') correlate to seafloor profiles shown in (c); a small (0.6 km long)  
694 transect labelled FP (Furrow profile) bisects a prominent, but fairly typical, seafloor furrow and correlates with the ‘Furrow  
695 profile’ in (c). **(b)** Geomorphic map depicting the geographical locations of the sinuous ridges, corrugated ridge and core  
696 locations on the Porcupine Bank and Slyne Trough. Transect A-A' corresponds with the sedimentary profile provided in the  
697 interpretation section. **(c)** Seafloor profiles derived from transects in (a). Profile X-X' is >18 km long and bisects three  
698 prominent sinuous ridges (red arrows) and possibly two subtle ridges (blue dotted arrows) to the north and south of core 43.  
699 Y-Y' and Z-Z' bisect large ridges within the Slyne Trough near cores 44 and 45, respectively; both elucidate areas of  
700 intense furrowing on the southern flanks of the ridges. Furrows on the southern flanks of ridges are visible on all three  
701 profiles. The furrow profile reveals a depth of ~10 m and flanking berms >3 m high.

702

703 Figure 3: Representative x-radiograph facies. **(a)** Horizontally-bedded sand in Core 45; black arrows highlight some of the  
704 prominent horizontal structures. The unit also fines upwards and has less biogenic material at its top. **(b)** Upward fining  
705 sand with areas of bioturbation (prominent burrows outlined with white dotted lines) in Core 42. **(c)** Massive, clast-  
706 supported diamicton from Core 42. Diffuse lower contact with underlying Dmm diamicton is highlighted (black dashed  
707 line). **(d)** Massive, matrix-supported diamicton in Core 44.

708

709 Figure 4: Core 42 sedimentary data; **(a)** true-colour photograph; **(b)** X-radiograph structure sketch; red boxes indicate  
710 locations of x-radiograph facies examples (Fig. 3b, c); **(c)** sedimentary log including lithofacies codes (Table 2) and  
711 calibrated radiocarbon age ranges where applicable (calcareous sample material symbol marks depth below seafloor; refer to  
712 Table 5 for specific radiocarbon data). Lithofacies association (LFA) bar correlates with sedimentary data and stratigraphic  
713 profile in interpretation section (Fig. 9). Physical and sedimentological properties are plotted against depth. Sand, silt and  
714 clay percentages are shown as pie charts, centred at appropriate depth intervals. The smoothed average magnetic  
715 susceptibility value is shown as a green line.

716

717 Figure 5: Core 43 sedimentary data; **(a)** true-colour photograph; **(b)** X-radiograph structure sketch; **(c)** sedimentary log  
718 including lithofacies codes (Table 2). Lithofacies association (LFA) bar correlates with sedimentary data and stratigraphic  
719 profile in interpretation section (Fig. 9). Sand, silt and clay percentages are shown as pie charts, centred at appropriate depth  
720 intervals. Refer to Figure 4 for legend.

721

722 Figure 6: Core 44 sedimentary data; **(a)** true-colour photograph; **(b)** X-radiograph structure sketch; red box indicates location  
723 of x-radiograph facies example (Fig. 3d); **(c)** sedimentary log including lithofacies codes (Table 2) and calibrated  
724 radiocarbon age ranges where applicable (calcareous sample material symbol marks depth below seafloor; refer to Table 5  
725 for specific radiocarbon data). Lithofacies association (LFA) bar correlates with sedimentary data and stratigraphic profile  
726 in discussion section (Fig. 9). Sand, silt and clay percentages are shown as pie charts, centred at appropriate depth intervals.  
727 Refer to Figure 4 for legend.

728

729 Figure 7: Core 45 sedimentary data; **(a)** true-colour photograph; **(b)** X-radiograph structure sketch; red box indicates location  
730 of x-radiograph facies example (Fig. 3a); **(c)** sedimentary log including lithofacies codes (Table 2) and calibrated  
731 radiocarbon age ranges where applicable (calcareous sample material symbol marks depth below seafloor; refer to Table 5  
732 for specific radiocarbon data). Lithofacies association (LFA) bar correlates with sedimentary data and stratigraphic profile  
733 in interpretation section (Fig. 9). Physical and sedimentological properties are plotted against depth. Sand, silt and clay  
734 percentages are shown as pie charts, centred at appropriate depth intervals. The smoothed average magnetic susceptibility  
735 value is shown as a green line. Refer to Figure 4 for legend.

736

737 Figure 8: Graphs displaying benthic-foraminifera diversity indices and total-count foraminifera statistics. Calibrated AMS  
738 radiocarbon ages are provided to the left of the diversity plots (Table 4). Stratigraphically-correlated lithofacies and  
739 lithofacies associations are shown on the right. Abbreviations: PTr = percentage of planktonic individuals; SDr = ratio of  
740 severely damaged; LFA = lithofacies association.

741

742 Figure 9: Graphs of relative abundances (shown as a percent along abscissae) for select benthic foraminifera species.  
743 Species are grouped into three palaeoenvironment species groups identified based on modern habitat preferences (see text  
744 for details). Calibrated AMS radiocarbon ages are provided to the left of the abundance plots (Table 4). Note that abscissae  
745 dimensions are only plotted to a relative scale between species to better display changes in species with lower maximum  
746 relative abundances. Abbreviations: LFA = lithofacies association; C. leav. = *C. laevigata*; U. med. = *U. mediterranea*; B.  
747 marg. = *B. marginata*; D. marg. = *D. coronata*; T. angu. = *T. angulosa*; C. reni. = *C. reniforme*; E. clav. = *E. clavatum*.

748

749 Figure 10: Stratigraphic profile showing interpreted facies across transect A-A' (Fig. 2b). Core locations and lithofacies  
750 associations are marked by labelled, vertical bars that correlate with those in Figures 3, 4, 5, 6, 7 and 8. Arrows show  
751 locations of radiocarbon sample acquisition and calibrated results are provided.

752

753 Figure 11: depositional model schematic of glacial history on the Porcupine Bank and Slyne Trough, west of Ireland. **(a)**  
754 Maximum westward extent of BIIS reaches the Porcupine Bank  $\leq 24,720 \pm 260$  Cal BP. A terminal moraine/grounding-zone  
755 wedge forms from till. Loose glaciomarine diamicton forms proglacially from sediment plume suspension settling and  
756 sediment rain out (IRD). **(b)** Initial retreat moves ice margin east and uncoupling from the Slyne Trough allows the inflow  
757 of Atlantic water below the BIIS within  $24,720 \pm 260$  to  $19,182 \pm 155$  Cal BP. Minor readvances create ice shelf push ridges  
758 on the Porcupine Bank. A new grounding-zone wedge forms in the Slyne Trough. Loose glaciomarine diamicton is  
759 deposited proglacially and as sub-ice shelf rain out. Debris flows on the Porcupine Bank ridges are likely. **(c)** Sub-ice shelf  
760 and proglacial diamicton sedimentation continues. Ice shelf thins due to climate amelioration and continued Atlantic water  
761 inflow. Sea level rise and ice thinning causes rapid ice shelf break up  $\leq 19,182 \pm 155$  Cal BP, which deposits a clast-rich  
762 glaciomarine diamicton. Increased palaeocurrents winnow the glaciomarine sediment of fines. A new grounding-zone  
763 wedge forms farther to the east in the Slyne Trough. **(d)** Open water conditions emerge following ice shelf break up. A  
764 north-northeastward palaeocurrent concentrates iceberg drift into the Slyne Trough where iceberg keels scour the seafloor  
765 and butt against the southern slopes of grounding-zone wedges, moraines and push ridges. Note that for enhanced clarity,  
766 this schematic simplifies the orientation of Porcupine Bank and Slyne Trough ridges (cf. Fig. 2); also, relative elevations of  
767 ice thickness, sea level and bathymetry are drawn to optimise graphical clarity. Overlying sandy Holocene sediments  
768 deposited postglacially by bottom current reworking are not shown.

769

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1097

1098

1099 **Appendix 1**

1100 Table A1: foraminiferal diversity index data.

Core	Interval (cm bsf)	SDr (%)	PTr (%)	Fisher's $\alpha$	Dominance
42	36	18.04878	63.41463	5.304	0.1363
	58	9.973046	68.46361	5.232	0.1668
	66	12.97539	65.43624	4.785	0.379
	78	35.76159	21.52318	3.879	0.2627
	88	36.02484	65.99379	2.729	0.2584
	108	27.0979	56.46853	3.508	0.2968
	139	17.29323	59.54887	3.134	0.3251
	157	22.51256	50.25126	2.677	0.2335
43	28	13.66806	70.99024	4.04	0.1893
	44	17.24138	74.03017	5.53	0.2773
	65	11.78248	66.76737	4.639	0.2629
	85	16.66667	63.4058	2.794	0.3835
44	5	8.726415	56.25	3.948	0.1325
	27	10.36107	60.75353	4.772	0.1207
	46	16.15799	56.55296	5.872	0.1156
	80	12.66376	56.55022	5.533	0.1685
	120	8.439898	47.82609	5.872	0.1908
	139	16.08775	52.10238	5.382	0.1622
	180	25.15723	53.45912	5.702	0.1892
	223	19.7561	50.4878	5.916	0.1626
45	31	10.25358	53.47299	4.365	0.1465
	57	16.61491	48.91304	4.993	0.1229
	94	13.53383	48.87218	6.272	0.1076
	142	8.523909	54.67775	5.759	0.1265
	254	12.36559	51.43369	5.328	0.1129

1101

1102

1103 Table A2: Benthic foraminifera absolute abundances (number of individuals) and general micropaleontological data for  
 1104 cores 42 and 43. Species with >2% relative abundance in in at least one core (42, 43, 44, 45) in bold, >5% in bold and  
 1105 underlined. (Refer to Table A3 for core 44 and 45 data.)

Cm (bsf)	Core 42								Core 43			
	36	58	66	78	88	108	139	157	28	44	65	85
Species	Individuals								Individuals			
<i>Amphicoryna scalaris</i>	0	0	0	0	0	0	0	0	0	0	0	0
<i>Bigenerinanososaria</i>	2	0	0	0	0	0	0	0	0	1	1	0
<i>Buccella frigida</i>	1	0	0	3	0	0	0	0	0	0	0	0
<i>Bulimina elongata</i>	0	0	0	0	0	0	0	0	0	0	1	0
<b><u>Bulimina gibba</u></b>	<b><u>2</u></b>	<b><u>1</u></b>	<b><u>2</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>2</u></b>	<b><u>2</u></b>	<b><u>5</u></b>	<b><u>1</u></b>
<b><u>Bulimina marginata</u></b>	<b><u>6</u></b>	<b><u>8</u></b>	<b><u>1</u></b>	<b><u>2</u></b>	<b><u>1</u></b>	<b><u>2</u></b>	<b><u>3</u></b>	<b><u>2</u></b>	<b><u>10</u></b>	<b><u>7</u></b>	<b><u>6</u></b>	<b><u>4</u></b>
<i>Bulivina sp.</i>	1	2	2	0	0	0	0	0	0	3	0	0
<b><u>Cassidulina laevigata</u></b>	<b><u>27</u></b>	<b><u>19</u></b>	<b><u>10</u></b>	<b><u>2</u></b>	<b><u>3</u></b>	<b><u>15</u></b>	<b><u>24</u></b>	<b><u>70</u></b>	<b><u>27</u></b>	<b><u>14</u></b>	<b><u>2</u></b>	<b><u>3</u></b>
<b><u>Cassidulina obtuse</u></b>	<b><u>9</u></b>	<b><u>12</u></b>	<b><u>17</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>2</u></b>	<b><u>1</u></b>	<b><u>15</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>0</u></b>
<b><u>Cassidulina reniforme</u></b>	<b><u>8</u></b>	<b><u>3</u></b>	<b><u>1</u></b>	<b><u>4</u></b>	<b><u>2</u></b>	<b><u>3</u></b>	<b><u>6</u></b>	<b><u>7</u></b>	<b><u>2</u></b>	<b><u>5</u></b>	<b><u>6</u></b>	<b><u>3</u></b>
<b><u>Cibicides lobatula</u></b>	<b><u>46</u></b>	<b><u>59</u></b>	<b><u>183</u></b>	<b><u>101</u></b>	<b><u>67</u></b>	<b><u>65</u></b>	<b><u>61</u></b>	<b><u>46</u></b>	<b><u>66</u></b>	<b><u>63</u></b>	<b><u>106</u></b>	<b><u>113</u></b>
<b><u>Cibicides refulgens</u></b>	<b><u>38</u></b>	<b><u>45</u></b>	<b><u>15</u></b>	<b><u>40</u></b>	<b><u>35</u></b>	<b><u>15</u></b>	<b><u>3</u></b>	<b><u>104</u></b>	<b><u>2</u></b>	<b><u>5</u></b>	<b><u>12</u></b>	<b><u>13</u></b>
<i>Cibicoides pachyderma</i>	0	0	0	0	0	1	2	0	1	0	0	3
<i>Dentalina subsoluta</i>	0	0	0	1	0	0	0	0	0	0		0
<b><u>Discanomalina coronata</u></b>	<b><u>4</u></b>	<b><u>6</u></b>	<b><u>6</u></b>	<b><u>50</u></b>	<b><u>12</u></b>	<b><u>13</u></b>	<b><u>10</u></b>	<b><u>31</u></b>	<b><u>3</u></b>	<b><u>4</u></b>	<b><u>17</u></b>	<b><u>8</u></b>
<i>Eggerella bradyi</i>	0	0	1	0	0	0	0	0	0	0	0	0
<b><u>Elphidium excavatum clavatum</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>2</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>
<b><u>Elphidium excavatum selseyensis</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>3</u></b>	<b><u>2</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>
<i>Fissurina sp.</i>	3	3	0	0	0	0	0	0	2	1	1	0
<i>Gavelinopsis translucens</i>	0	0	0	0	1	0	0	0	0	0	0	0
<b><u>Globocassidulina subglobosa</u></b>	<b><u>2</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>1</u></b>	<b><u>5</u></b>	<b><u>2</u></b>	<b><u>2</u></b>	<b><u>4</u></b>	<b><u>1</u></b>	<b><u>2</u></b>	<b><u>1</u></b>	<b><u>0</u></b>
<i>Guttulina sp.</i>	0	0	0	0	0	0	0	0	0	0	0	1
<b><u>Gyroidinoides soldanii</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>16</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>
<i>Hyalinea balthica</i>	0	0	0	0	0	0	0	0	0	0	0	0
<i>Lagena sp.</i>	0	1	0	0	0	0	0	2	0	1	0	0
<i>Lagena striata</i>	0	0	0	1	0	1	1	0	0	1	1	0
<b><u>Lenticulina sp.</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>7</u></b>	<b><u>0</u></b>
<b><u>Melonis barleeanus</u></b>	<b><u>0</u></b>	<b><u>3</u></b>	<b><u>3</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>2</u></b>	<b><u>0</u></b>	<b><u>5</u></b>	<b><u>3</u></b>	<b><u>3</u></b>	<b><u>0</u></b>	<b><u>0</u></b>
<i>Miliammina fusca</i>	0	0	0	0	0	0	0	0	0	0	1	0
<i>Miliolinella chukchiensis</i>	0	0	0	0	0	0	0	0	0	0	0	0
<i>Nonionella turgida</i>	1	1	2	0	0	0	0	0	0	0	0	0
<i>Oolina caudigera</i>	0	0	0	0	0	0	0	0	0	1	0	0
<b><u>Planulina ariminensis</u></b>	<b><u>3</u></b>	<b><u>1</u></b>	<b><u>2</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>2</u></b>	<b><u>0</u></b>	<b><u>2</u></b>	<b><u>4</u></b>	<b><u>3</u></b>	<b><u>0</u></b>	<b><u>0</u></b>
<i>Pyrgo sp.</i>	0	0	0	0	0	0	0	0	0	0	0	0
<i>Pyrgo williamsoni</i>	0	0	2	0	0	0	0	0	0	0	0	0
<b><u>Quinqueloculina sp.</u></b>	<b><u>3</u></b>	<b><u>5</u></b>	<b><u>3</u></b>	<b><u>5</u></b>	<b><u>3</u></b>	<b><u>0</u></b>	<b><u>3</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>1</u></b>	<b><u>4</u></b>	<b><u>1</u></b>
<i>Reophax sp.</i>	0	0	0	0	0	0	0	0	0	0	0	0
<i>Sigmolites schlumbergeri</i>	0	0	0	0	0	0	0	0	0	0	0	0
<b><u>Textularia sp.</u></b>	<b><u>5</u></b>	<b><u>2</u></b>	<b><u>4</u></b>	<b><u>2</u></b>	<b><u>8</u></b>	<b><u>8</u></b>	<b><u>13</u></b>	<b><u>0</u></b>	<b><u>9</u></b>	<b><u>4</u></b>	<b><u>9</u></b>	<b><u>1</u></b>
<b><u>Trifarina angulosa</u></b>	<b><u>45</u></b>	<b><u>54</u></b>	<b><u>41</u></b>	<b><u>15</u></b>	<b><u>80</u></b>	<b><u>116</u></b>	<b><u>138</u></b>	<b><u>196</u></b>	<b><u>50</u></b>	<b><u>108</u></b>	<b><u>26</u></b>	<b><u>51</u></b>
<i>Triloculina tricarinata</i>	1	0	7	0	0	1	0	0	0	0	4	0
<b><u>Uvigerina mediterranea</u></b>	<b><u>17</u></b>	<b><u>6</u></b>	<b><u>1</u></b>	<b><u>6</u></b>	<b><u>1</u></b>	<b><u>1</u></b>	<b><u>0</u></b>	<b><u>8</u></b>	<b><u>9</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>0</u></b>
Total benthic foraminifera	225	234	309	237	219	249	270	495	208	241	220	202
Total planktonic foraminifera	390	508	585	65	425	323	396	500	509	687	442	350
Sample weight (mg)	148	137	138	679	169	100	45	99	68	84	177	138
Foraminifera/mg	4.2	5.4	6.5	0.4	3.8	5.7	15	10	11	11	3.7	4.0

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Table A3: Benthic foraminifera absolute abundances (number of individuals) and general micropaleontological data for cores 44 and 45. Species with >2% relative abundance in in at least one core (42, 43, 44, 45) in bold, >5% in bold and underlined. (Refer to Table A2 for core 42 and 43 data.)

Cm (bsf)	Core 44								Core 45					
	5	27	46	80	120	139	180	223	31	57	94	142	209	254
Species	Individuals								Individuals					
<i>Amphicoryna scalaris</i>	2	1	1	0	0	0	0	0	0	2	0	0	0	0
<i>Bigenerinanososaria</i>	2	2	2	0	1	0	0	0	4	6	1	0	0	1
<i>Buccella frigida</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Bulimina elongata</i>	0	0	0	0	0	1	0	0	0	0	0	0	0	0
<b><u>Bulimina gibba</u></b>	<b>4</b>	<b>0</b>	<b>6</b>	<b>5</b>	<b>12</b>	<b>10</b>	<b>7</b>	<b>8</b>	<b>2</b>	<b>3</b>	<b>13</b>	<b>8</b>	<b>11</b>	<b>3</b>
<b><u>Bulimina marqinata</u></b>	<b>43</b>	<b>29</b>	<b>20</b>	<b>6</b>	<b>7</b>	<b>5</b>	<b>6</b>	<b>4</b>	<b>65</b>	<b>69</b>	<b>6</b>	<b>9</b>	<b>11</b>	<b>10</b>
<i>Bulivina sp.</i>	10	9	3	2	3	10	4	4	17	7	7	6	5	2
<b><u>Cassidulina laevigata</u></b>	<b>77</b>	<b>47</b>	<b>30</b>	<b>12</b>	<b>20</b>	<b>14</b>	<b>23</b>	<b>13</b>	<b>79</b>	<b>55</b>	<b>23</b>	<b>19</b>	<b>34</b>	<b>23</b>
<b><u>Cassidulina obtuse</u></b>	<b>9</b>	<b>5</b>	<b>3</b>	<b>2</b>	<b>3</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>5</b>	<b>1</b>	<b>3</b>	<b>2</b>	<b>5</b>	<b>8</b>
<b><u>Cassidulina reniforme</u></b>	<b>0</b>	<b>0</b>	<b>1</b>	<b>8</b>	<b>5</b>	<b>7</b>	<b>4</b>	<b>11</b>	<b>0</b>	<b>11</b>	<b>14</b>	<b>5</b>	<b>9</b>	<b>6</b>
<b><u>Cibicides lobatula</u></b>	<b>51</b>	<b>32</b>	<b>52</b>	<b>63</b>	<b>77</b>	<b>87</b>	<b>82</b>	<b>66</b>	<b>26</b>	<b>27</b>	<b>38</b>	<b>54</b>	<b>58</b>	<b>69</b>
<b><u>Cibicides refulgens</u></b>	<b>5</b>	<b>2</b>	<b>13</b>	<b>7</b>	<b>3</b>	<b>20</b>	<b>14</b>	<b>7</b>	<b>7</b>	<b>12</b>	<b>18</b>	<b>16</b>	<b>19</b>	<b>4</b>
<i>Cibicoides pachyderma</i>	1	0	0	0	1	0	0	0	2	0	0	1	0	0
<i>Dentalina subsoluta</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<b><u>Discanomalina coronata</u></b>	<b>1</b>	<b>1</b>	<b>5</b>	<b>9</b>	<b>5</b>	<b>8</b>	<b>2</b>	<b>5</b>	<b>3</b>	<b>2</b>	<b>1</b>	<b>4</b>	<b>10</b>	<b>8</b>
<i>Eggerella bradyi</i>	0	1	0	0	0	0	1	0	0	0	0	0	0	0
<b><u>Elphidium excavatum clavatum</u></b>	<b>0</b>	<b>0</b>	<b>1</b>	<b>10</b>	<b>5</b>	<b>8</b>	<b>6</b>	<b>7</b>	<b>0</b>	<b>6</b>	<b>8</b>	<b>5</b>	<b>9</b>	<b>9</b>
<b><u>Elphidium excavatum selseyensis</u></b>	<b>0</b>	<b>5</b>	<b>4</b>	<b>2</b>	<b>0</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>6</b>	<b>6</b>	<b>4</b>
<i>Fissurina sp.</i>	0	2	0	0	0	0	0	0	3	0	0	0	0	0
<i>Gavelinopsis translucens</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<b><u>Globocassidulina subglobosa</u></b>	<b>0</b>	<b>0</b>	<b>1</b>	<b>2</b>	<b>0</b>	<b>2</b>	<b>1</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>1</b>	<b>3</b>	<b>2</b>	<b>0</b>
<i>Guttulina sp.</i>	0	0	0	0	0	0	0	0	0	1	0	0	1	0
<b><u>Gyroidinoides soldanii</u></b>	<b>0</b>	<b>0</b>	<b>2</b>	<b>0</b>	<b>0</b>	<b>1</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>2</b>	<b>0</b>	<b>3</b>	<b>0</b>
<i>Hyalinea balthica</i>	0	0	1	0	0	1	0	0	2	0	0	0	0	0
<i>Lagena sp.</i>	0	0	0	0	0	0	0	0	0	0	0	0	2	0
<i>Lagena striata</i>	1	0	0	0	0	0	0	0	2	0	1	0	1	1
<b><u>Lenticulina sp.</u></b>	<b>2</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>	<b>2</b>	<b>1</b>	<b>5</b>	<b>0</b>	<b>1</b>	<b>1</b>	<b>2</b>	<b>0</b>	<b>0</b>
<b><u>Melonis barleeanus</u></b>	<b>2</b>	<b>1</b>	<b>2</b>	<b>1</b>	<b>3</b>	<b>4</b>	<b>4</b>	<b>7</b>	<b>7</b>	<b>5</b>	<b>7</b>	<b>8</b>	<b>7</b>	<b>1</b>
<i>Miliammina fusca</i>	0	1	1	3	0	0	0	2	1	0	0	1	1	0
<i>Miliolinella chukchiensis</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	1
<i>Nonionella turgida</i>	0	0	0	0	0	0	1	0	0	0	0	0	0	0
<i>Oolina caudigera</i>	0	0	0	0	0	0	0	2	0	0	0	0	0	0
<b><u>Planulina ariminensis</u></b>	<b>27</b>	<b>18</b>	<b>13</b>	<b>4</b>	<b>1</b>	<b>4</b>	<b>1</b>	<b>3</b>	<b>23</b>	<b>11</b>	<b>3</b>	<b>3</b>	<b>8</b>	<b>1</b>
<i>Pyrgo sp.</i>	0	0	0	0	0	0	0	0	0	6	0	0	0	0
<i>Pyrgo williamsoni</i>	0	0	0	1	0	0	2	0	0	0	0	0	0	0
<b><u>Quinqueloculina sp.</u></b>	<b>0</b>	<b>0</b>	<b>2</b>	<b>4</b>	<b>2</b>	<b>5</b>	<b>3</b>	<b>4</b>	<b>0</b>	<b>0</b>	<b>3</b>	<b>4</b>	<b>7</b>	<b>6</b>
<i>Reophax sp.</i>	0	0	0	0	1	0	0	1	0	0	3	0	0	1
<i>Sigmoilopsis schlumbergeri</i>	0	0	0	0	2	3	1	2	0	1	1	4	4	1
<b><u>Textularia sp.</u></b>	<b>24</b>	<b>19</b>	<b>11</b>	<b>3</b>	<b>6</b>	<b>6</b>	<b>5</b>	<b>2</b>	<b>15</b>	<b>13</b>	<b>2</b>	<b>3</b>	<b>0</b>	<b>5</b>
<b><u>Trifarina anquilosa</u></b>	<b>45</b>	<b>33</b>	<b>28</b>	<b>46</b>	<b>33</b>	<b>46</b>	<b>37</b>	<b>39</b>	<b>52</b>	<b>36</b>	<b>38</b>	<b>41</b>	<b>48</b>	<b>50</b>
<i>Triloculina tricarinata</i>	0	0	0	1	0	0	0	0	0	0	0	1	0	0
<b><u>Uvigerina mediterranea</u></b>	<b>67</b>	<b>40</b>	<b>38</b>	<b>6</b>	<b>13</b>	<b>16</b>	<b>14</b>	<b>7</b>	<b>105</b>	<b>53</b>	<b>6</b>	<b>13</b>	<b>10</b>	<b>12</b>
Total benthic foraminifera	371	250	242	200	204	262	222	203	422	329	204	218	271	226
Total planktonic forams.	477	387	315	259	187	285	255	207	485	315	195	263	287	215
Sample weight (mg)	83	88	105	143	100	84	162	160	82	99	132	152	186	144
Foraminifera/mg	10	7.3	5.3	3.2	3.9	6.5	2.9	2.6	11	6.5	3.0	3.2	3.0	3.1

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Figure  
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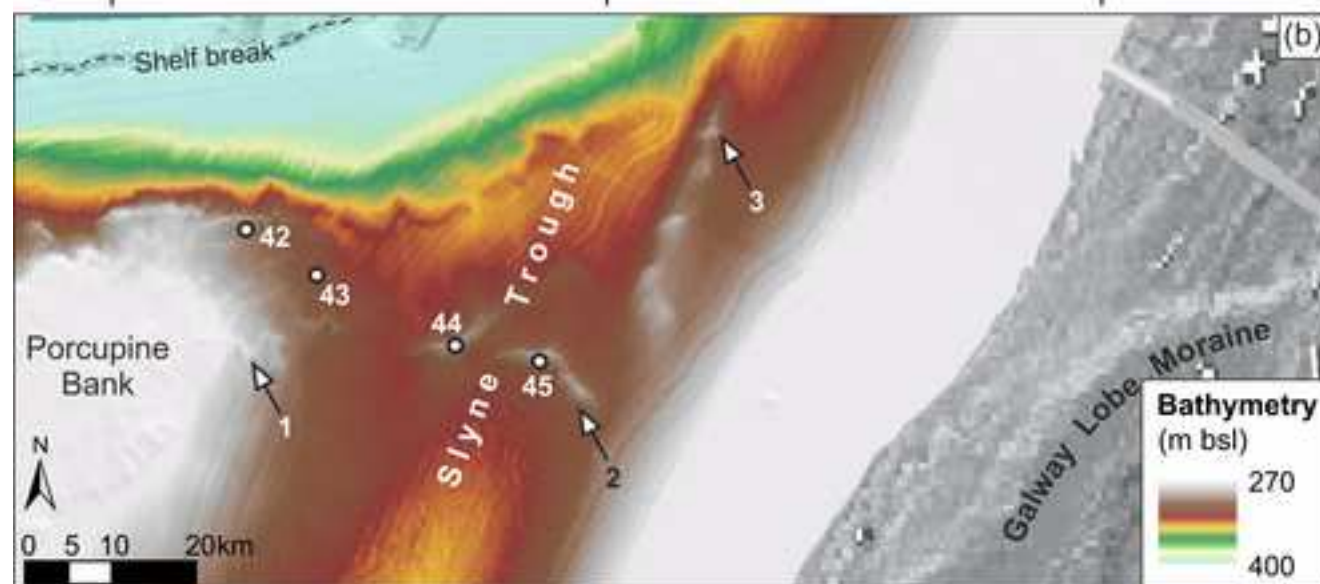
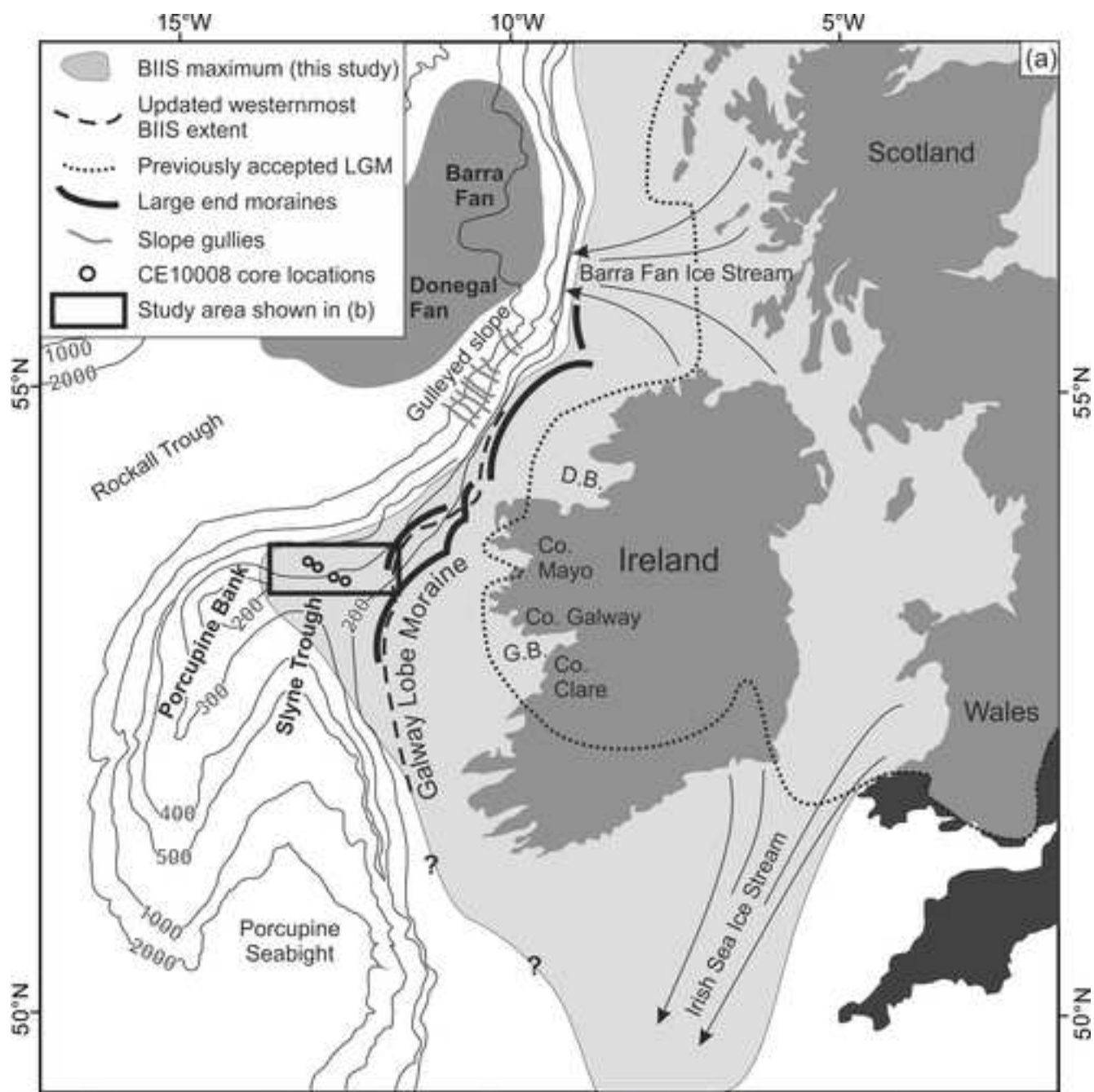


Figure  
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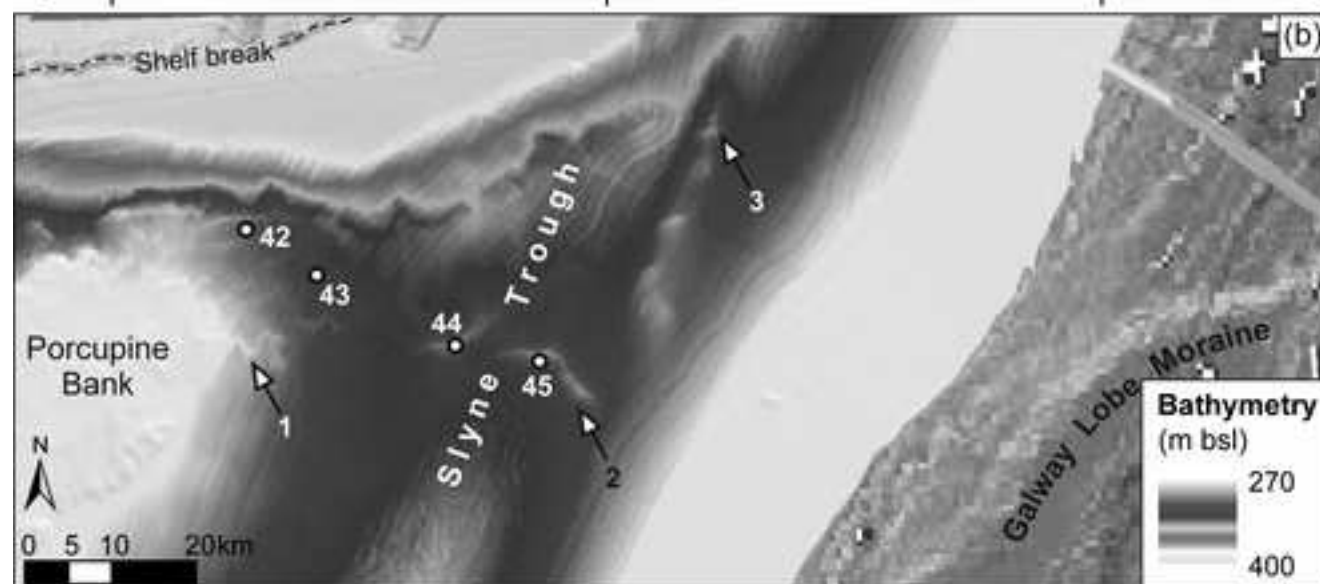
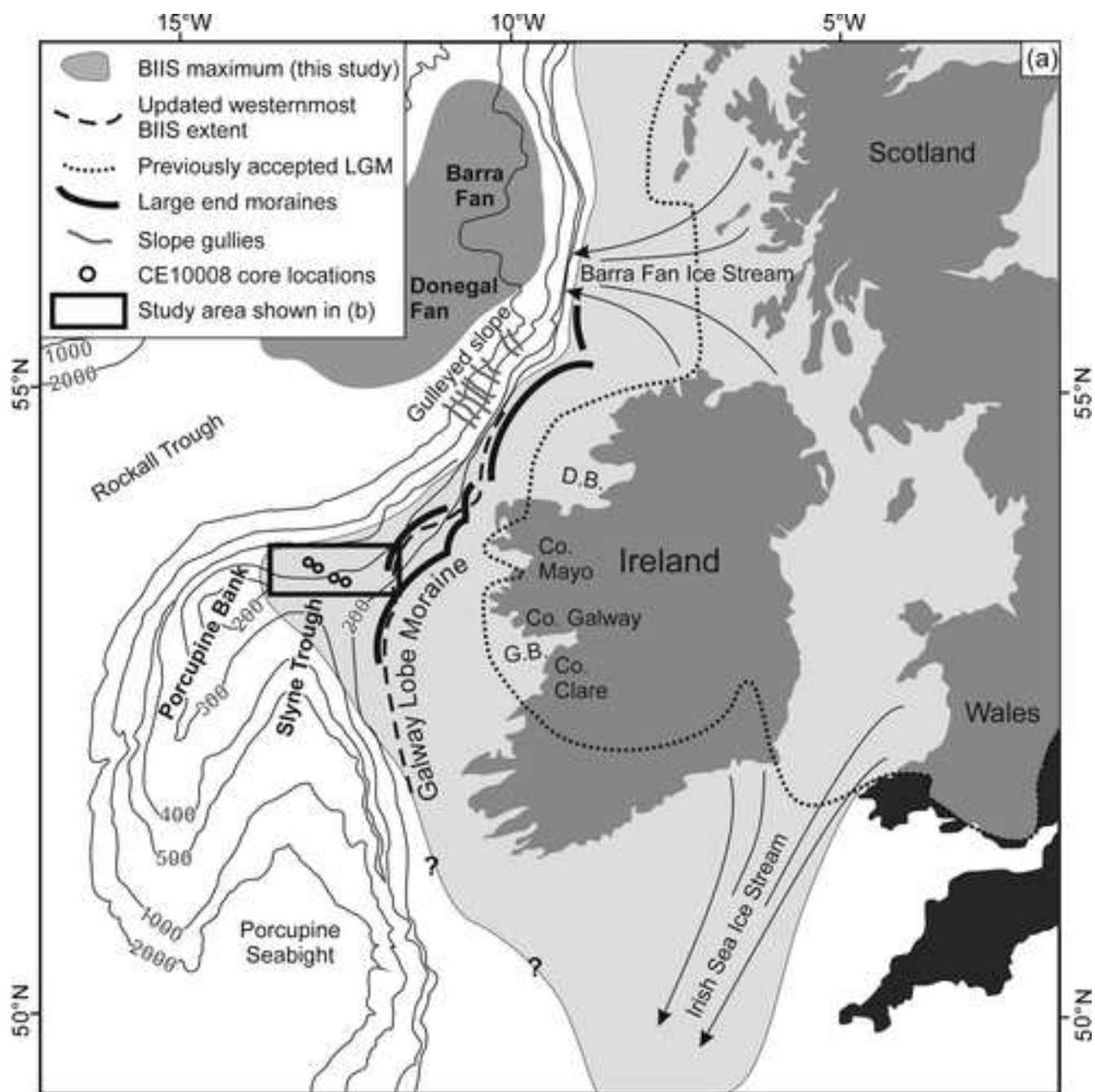


Figure  
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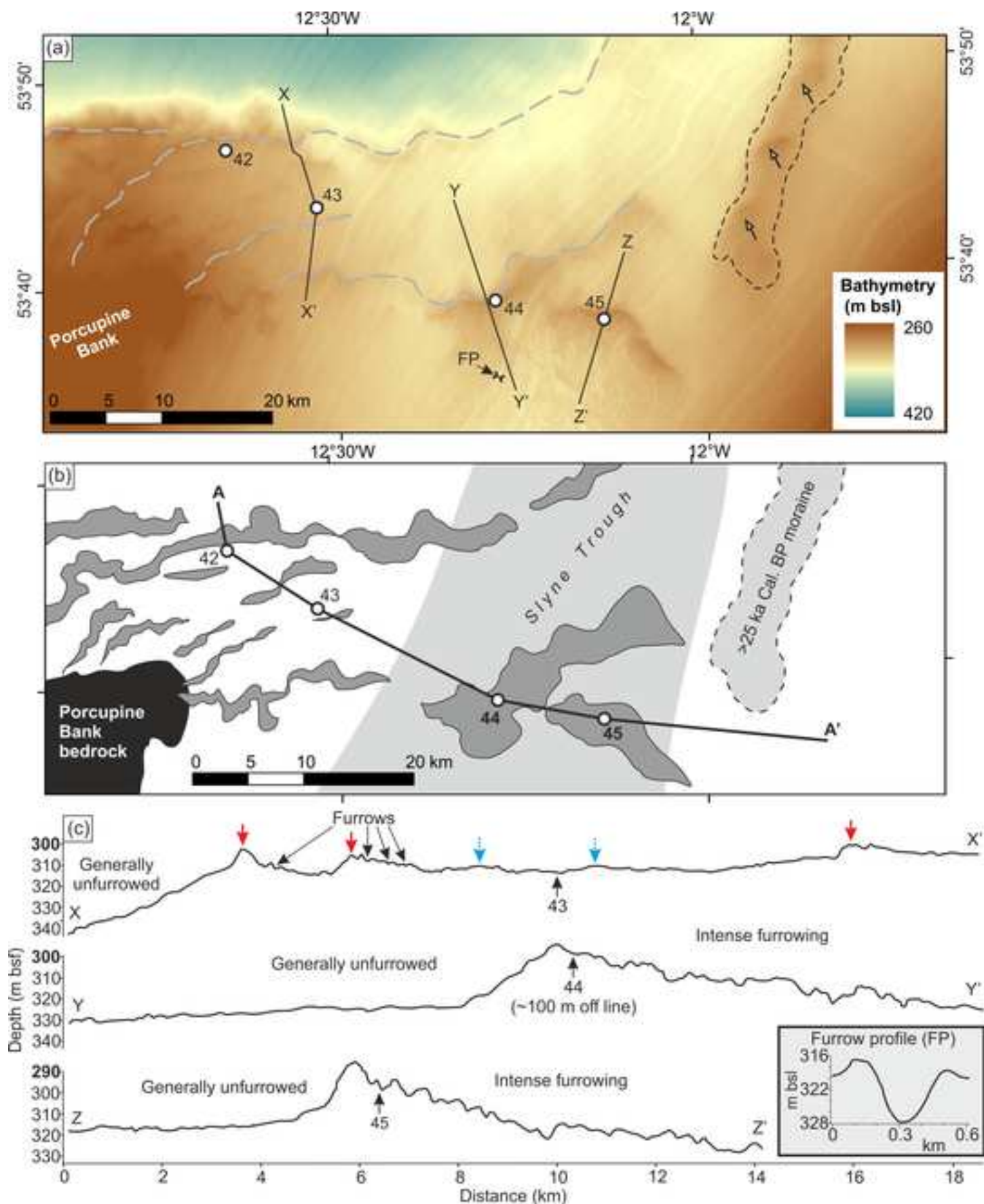
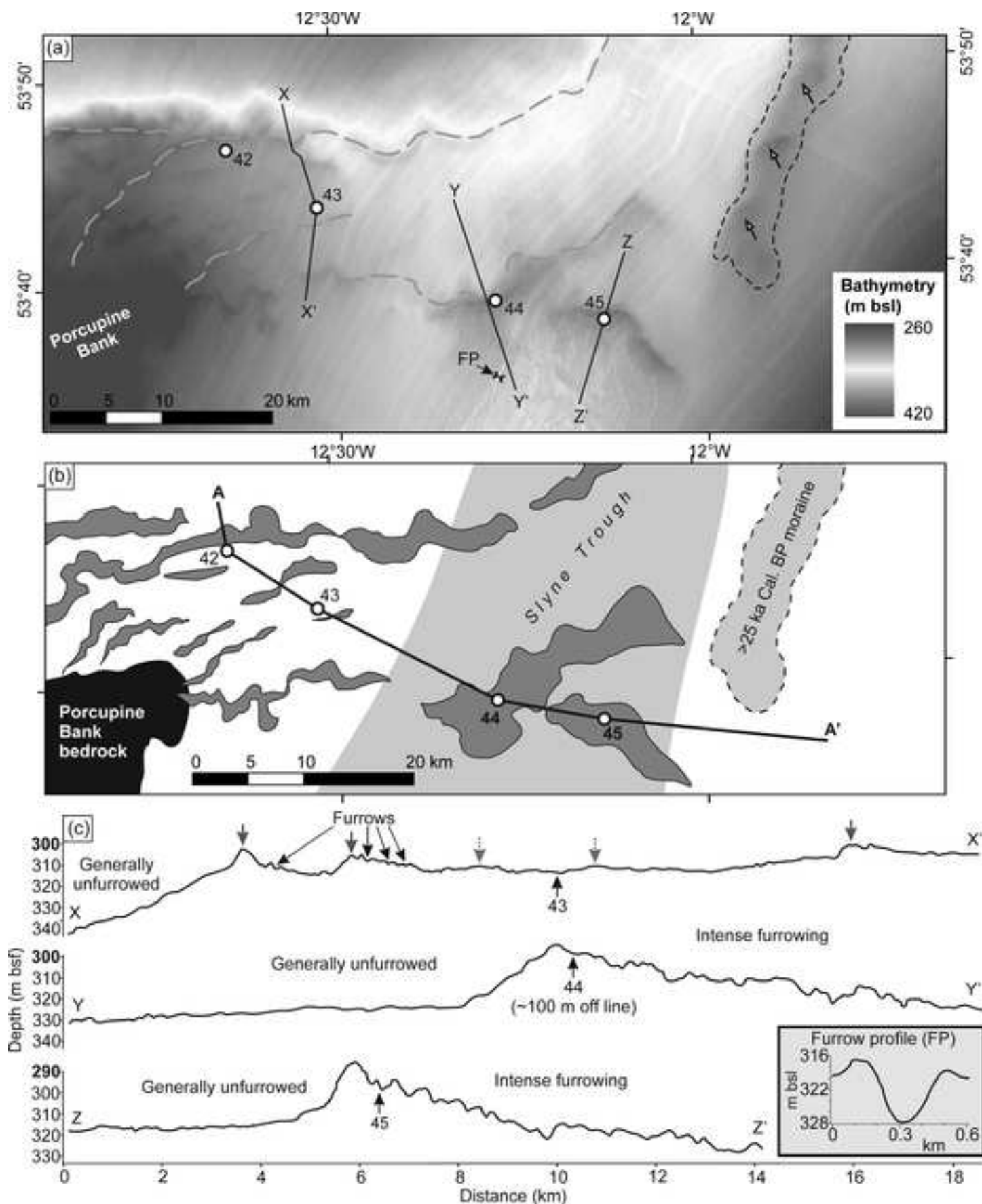


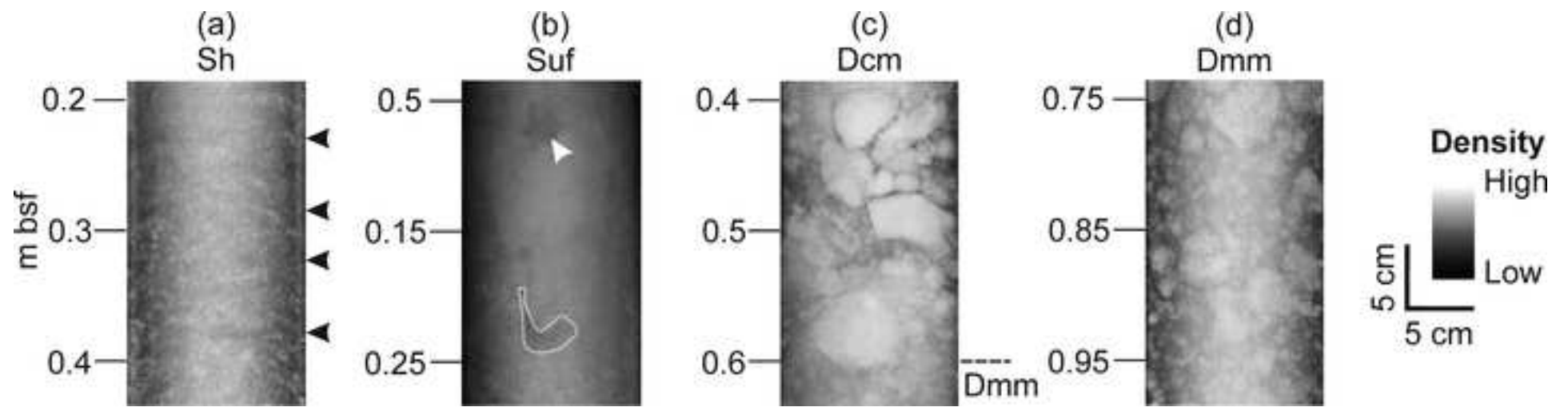


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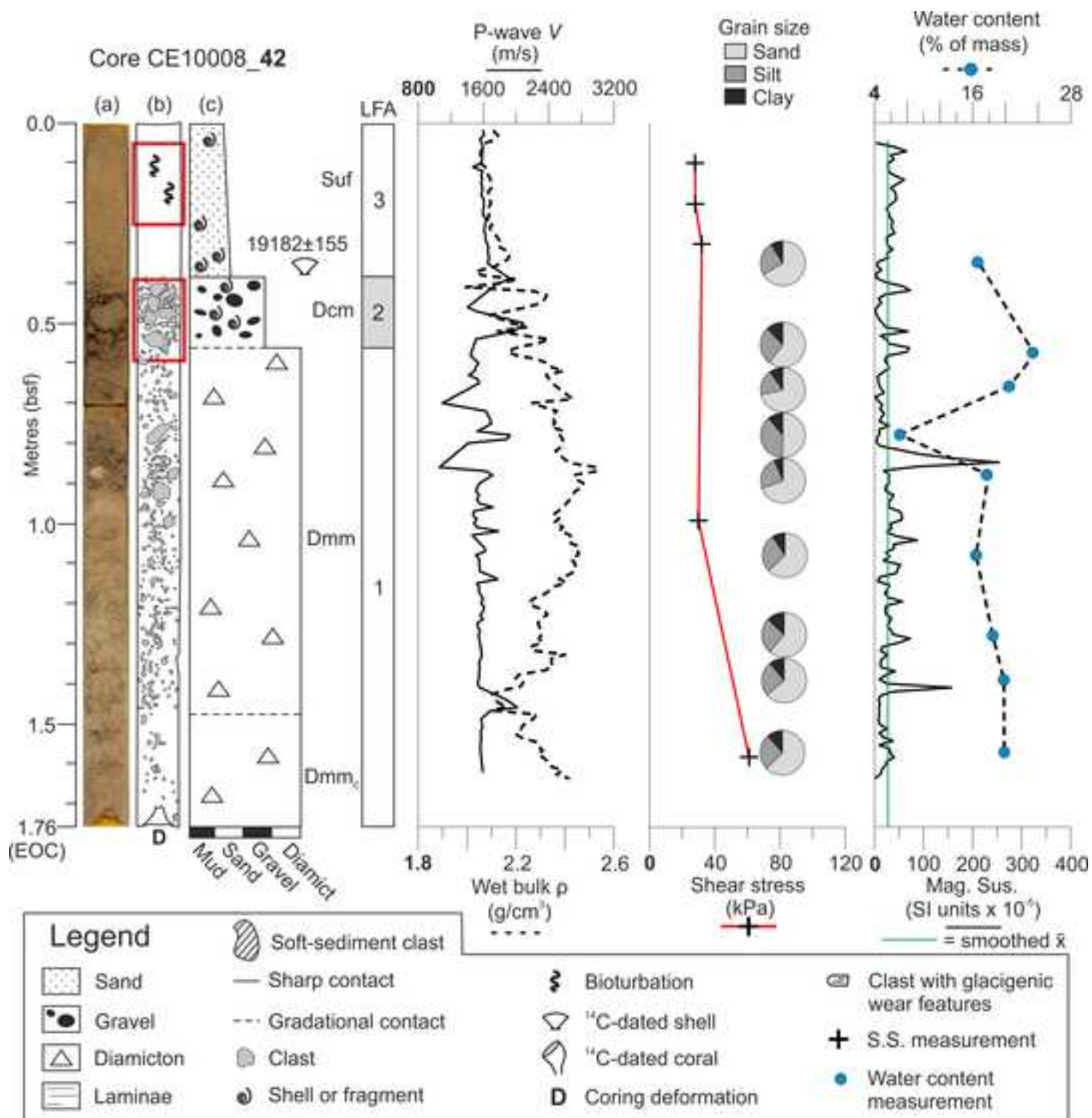
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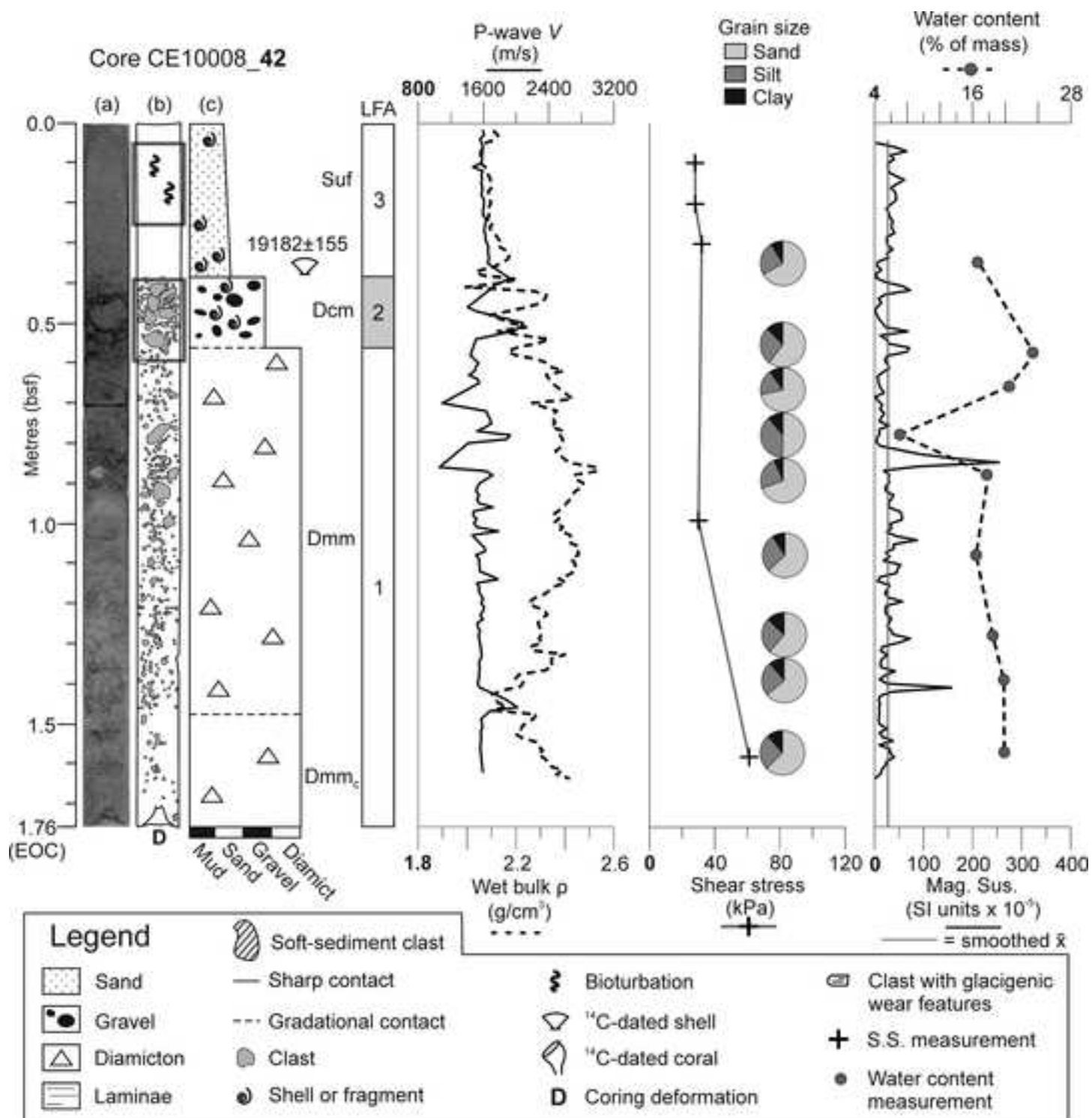




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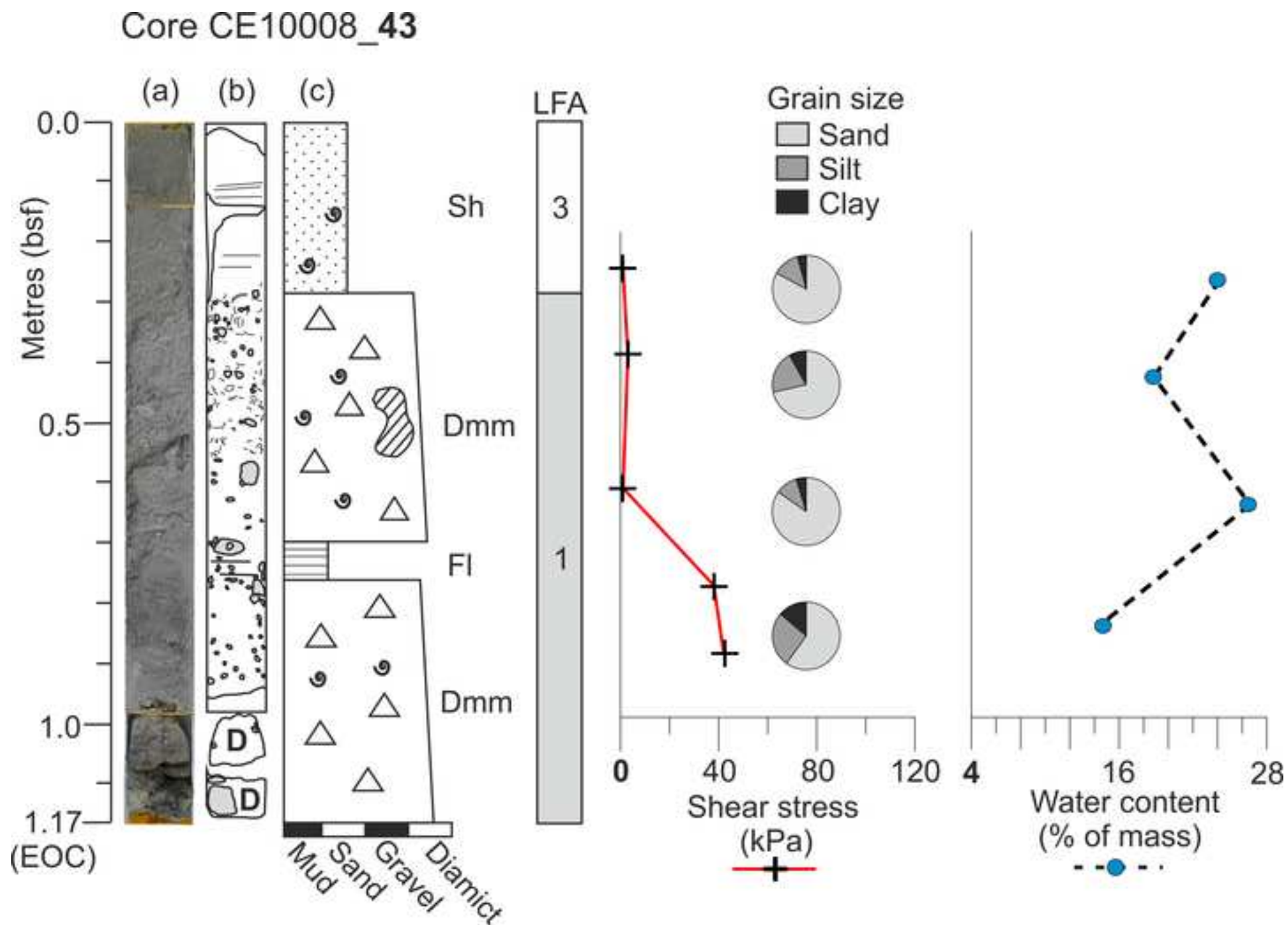




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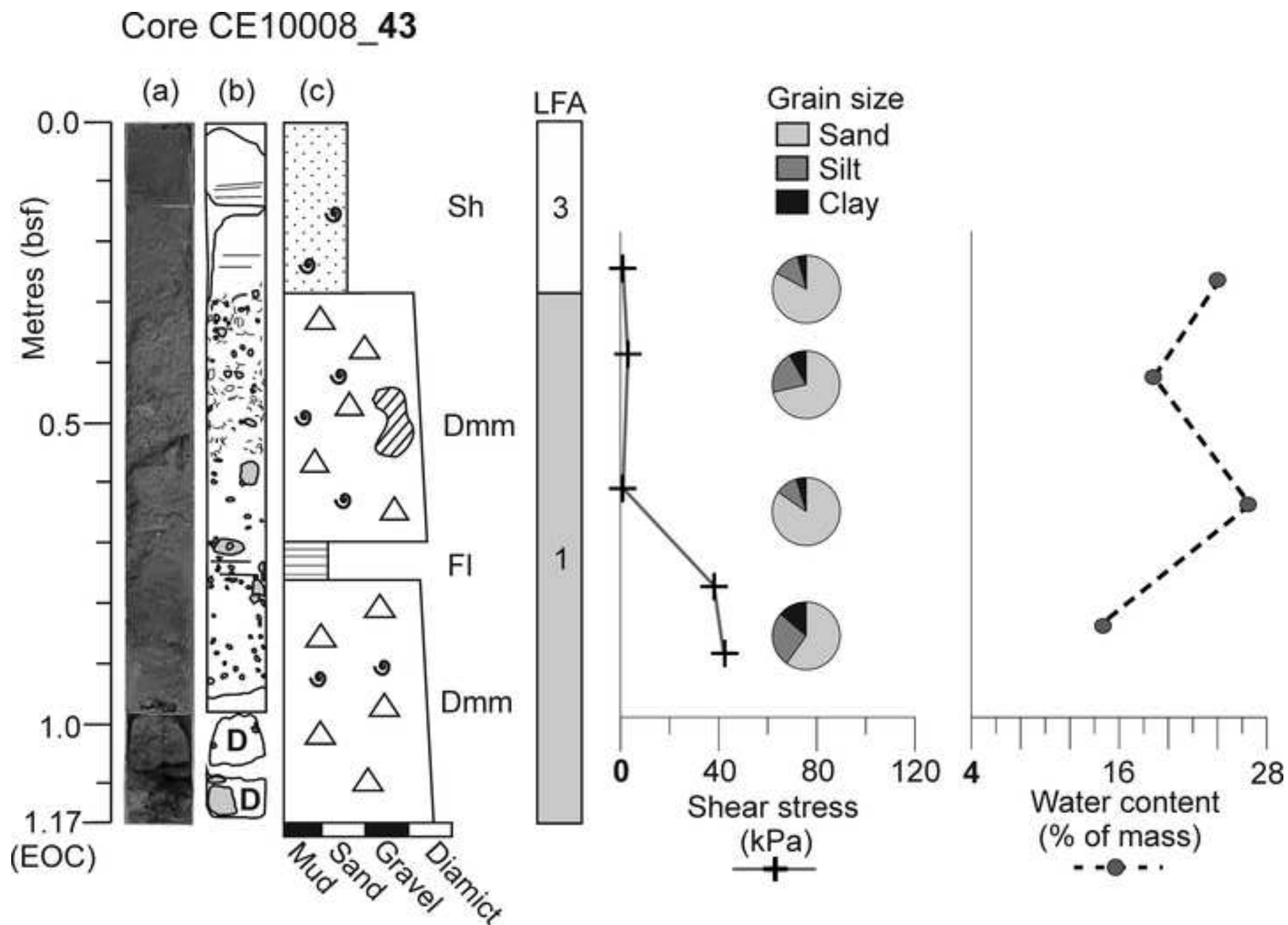


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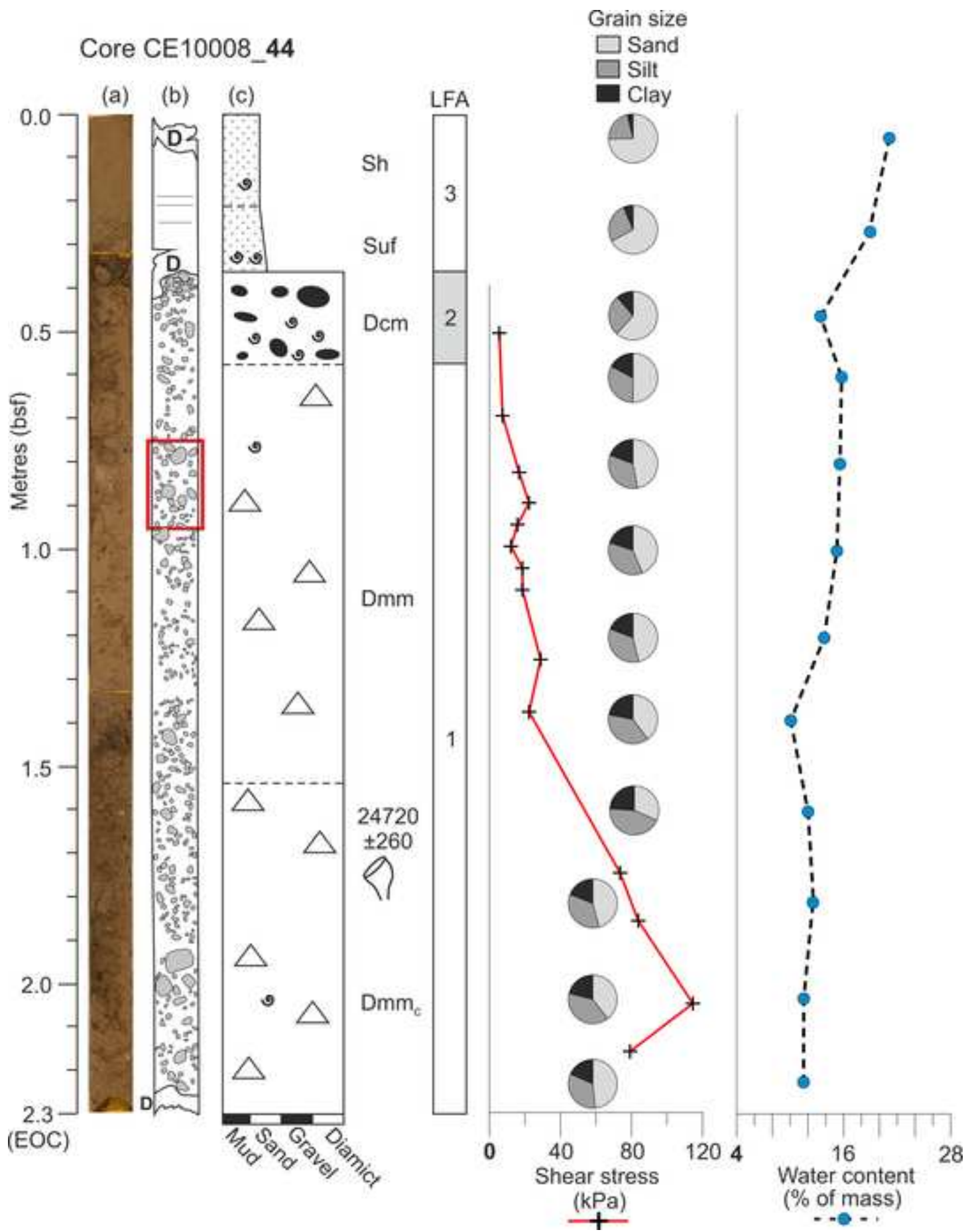


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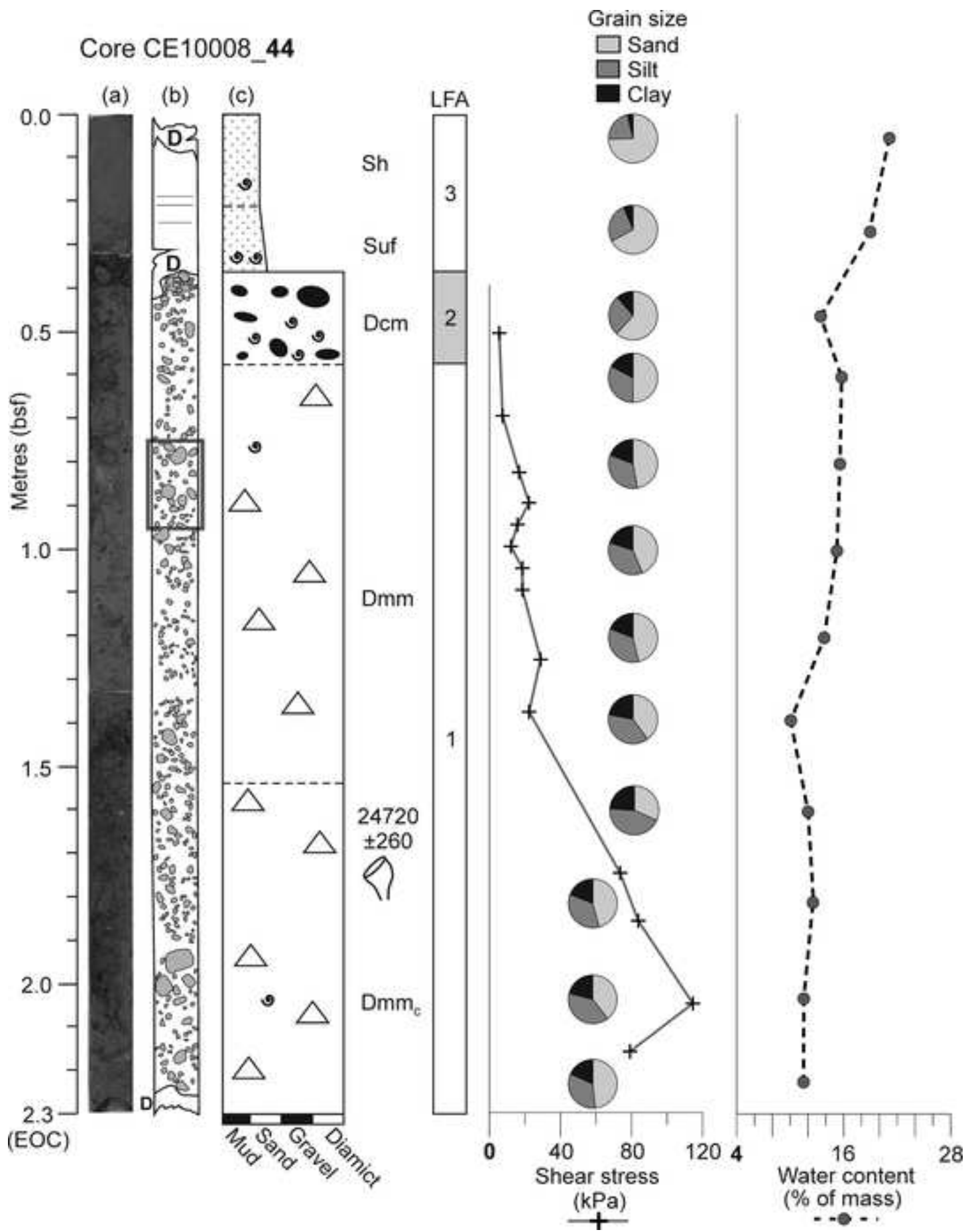


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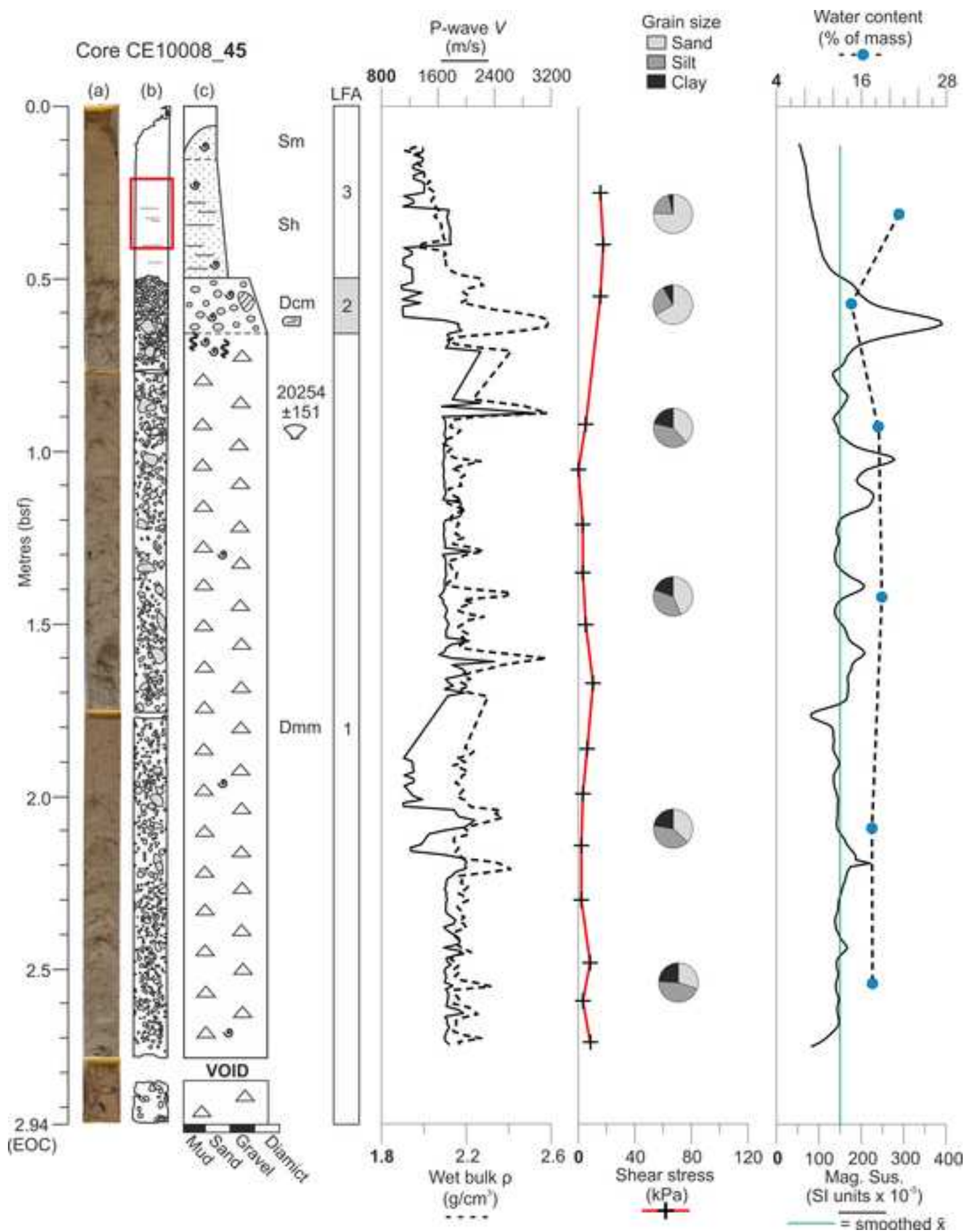




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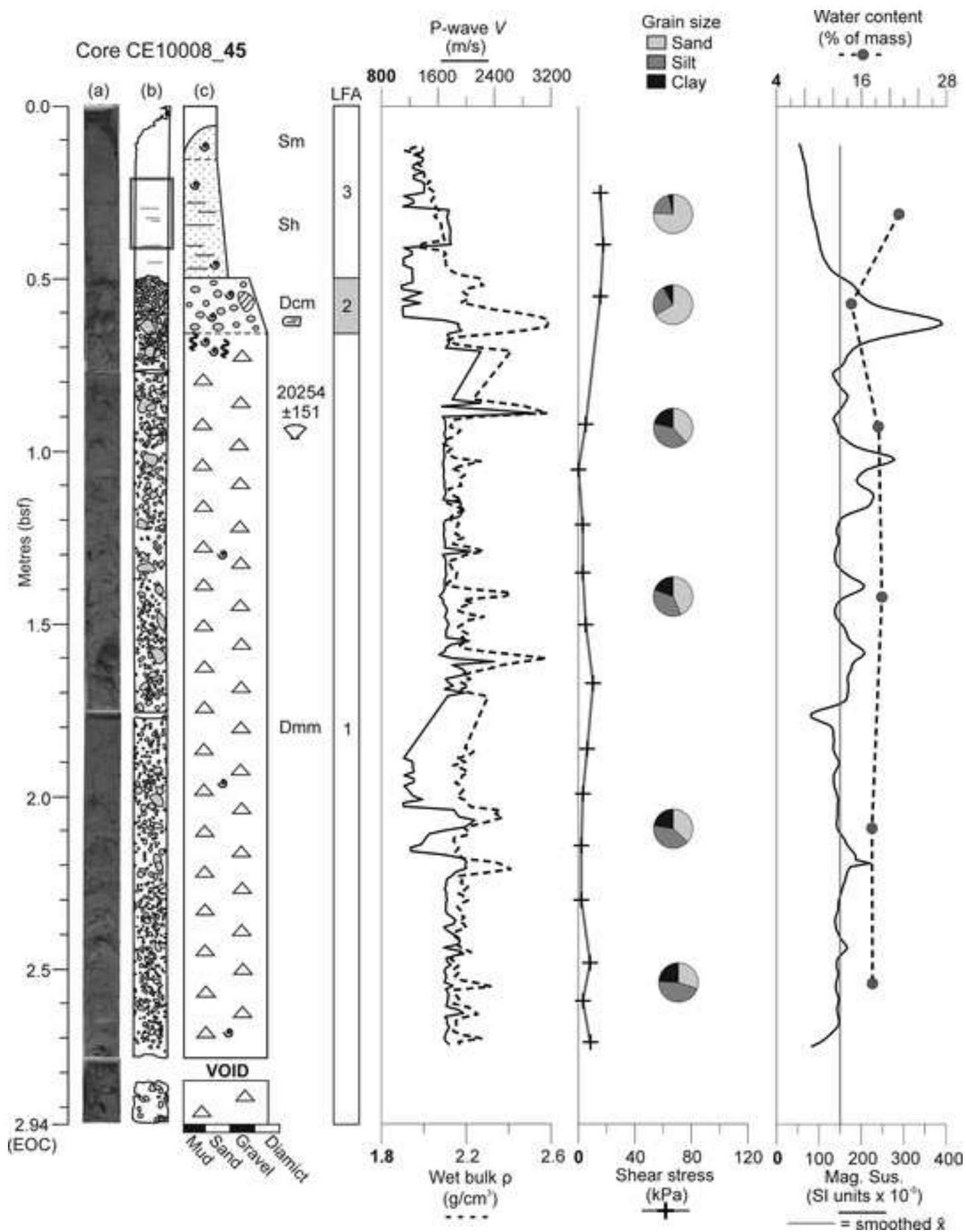
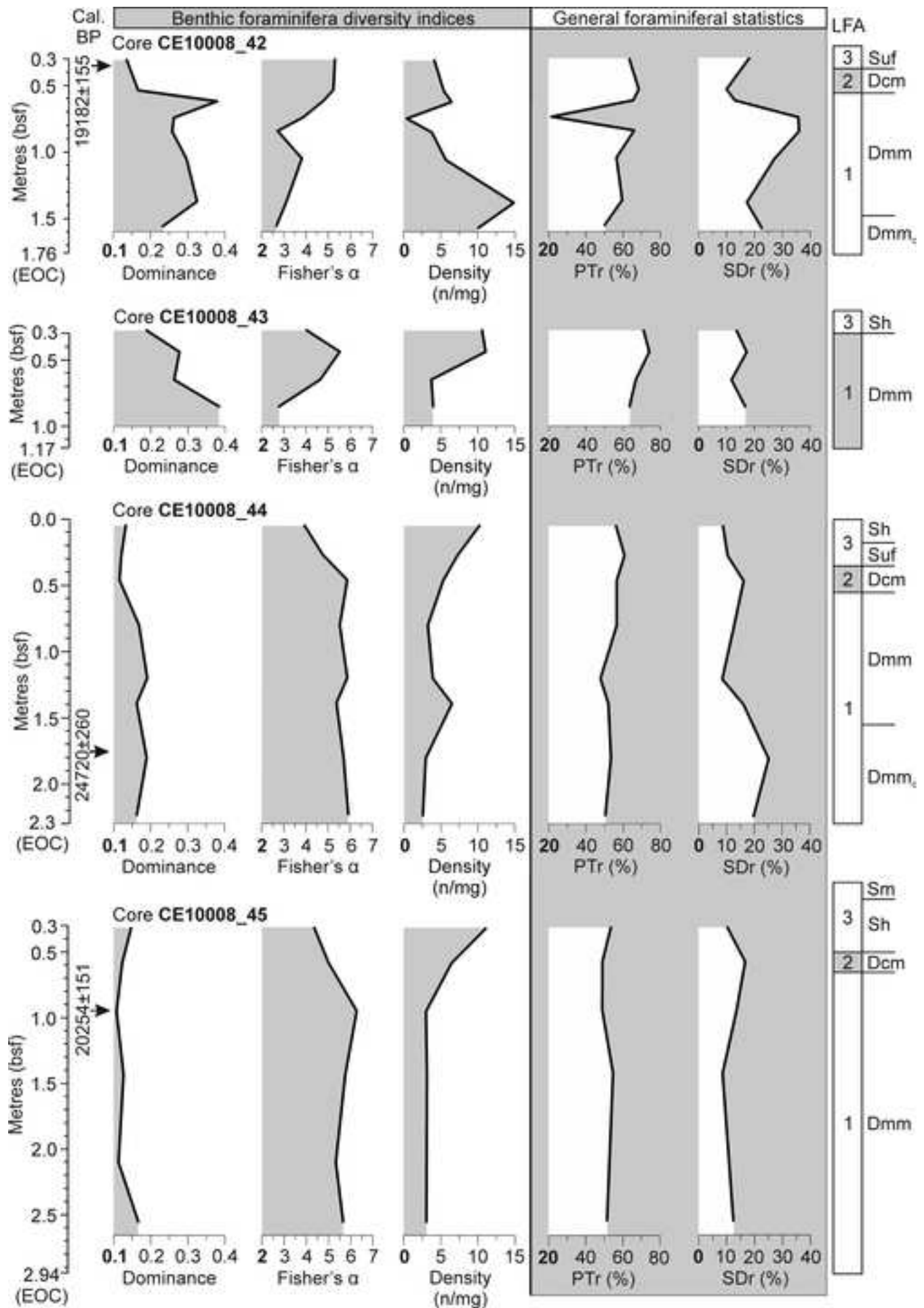


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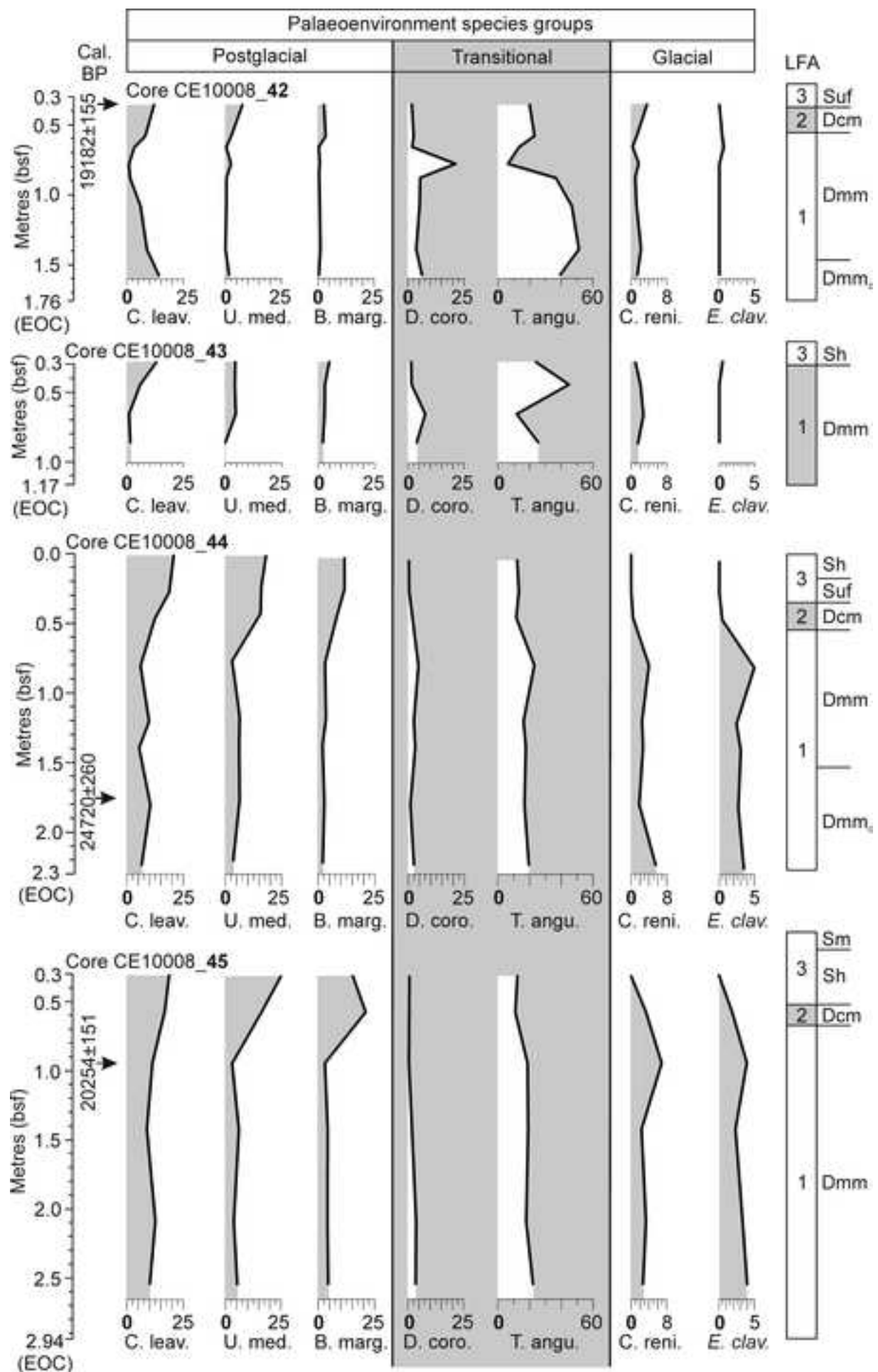


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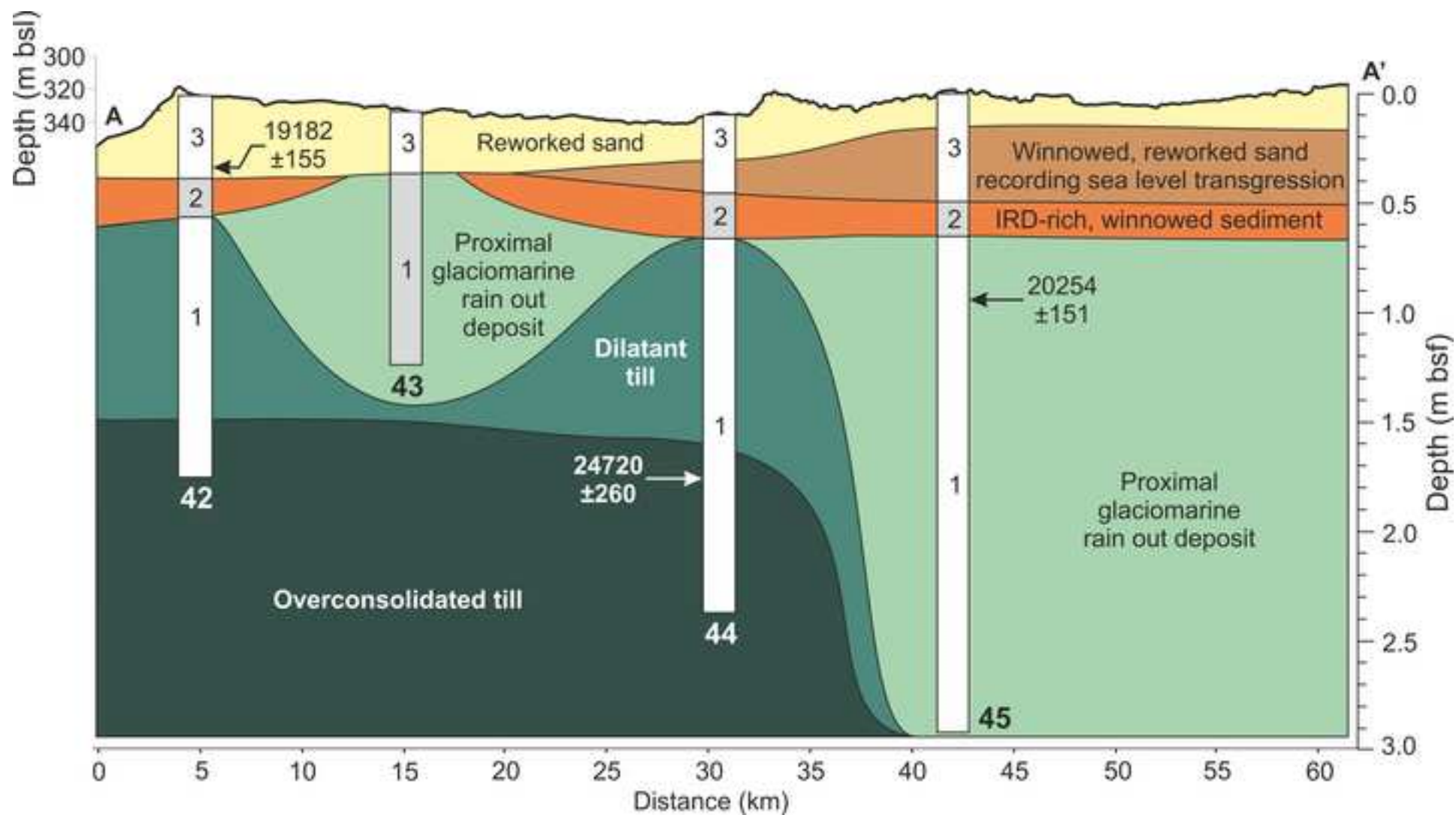
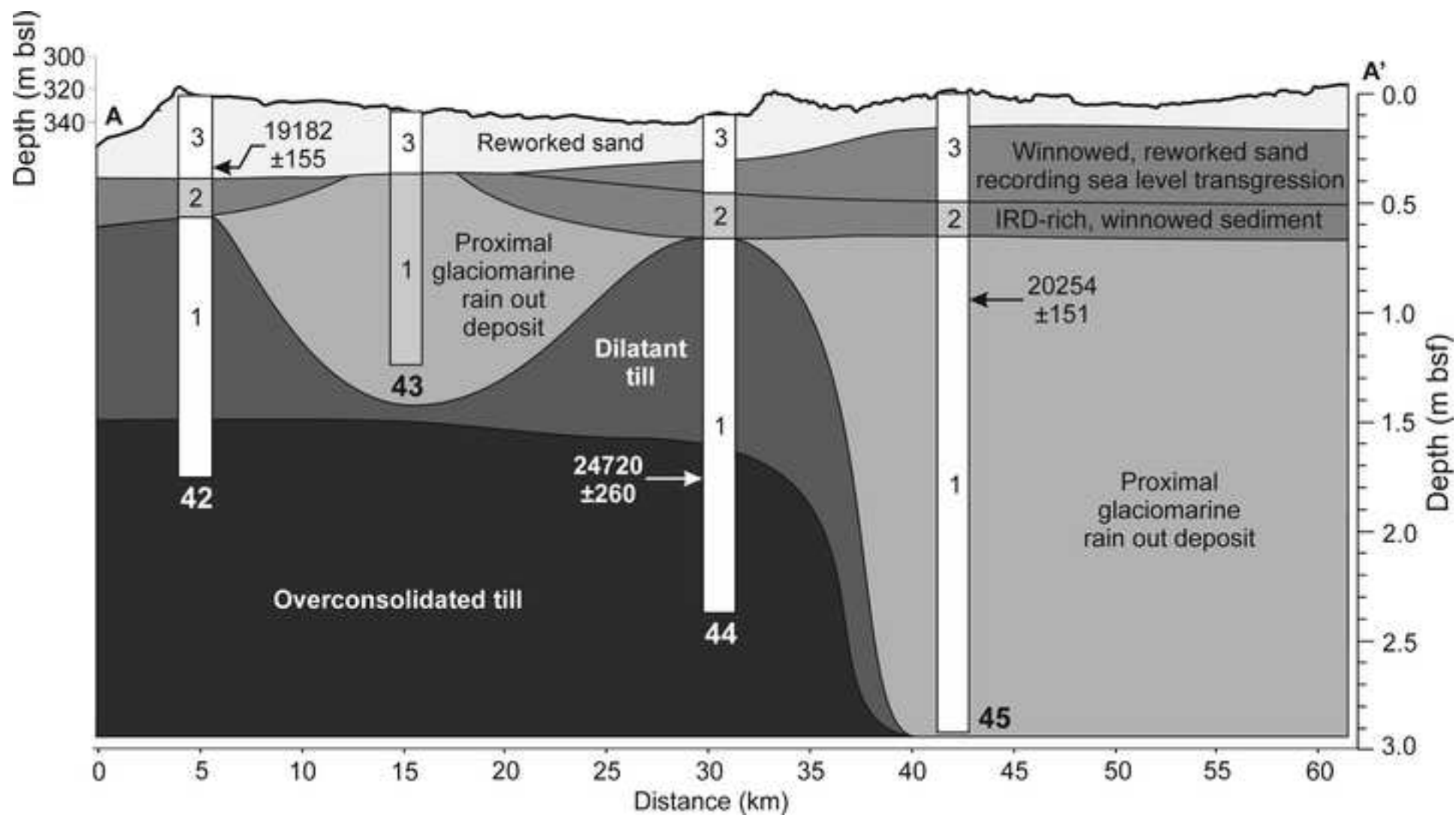


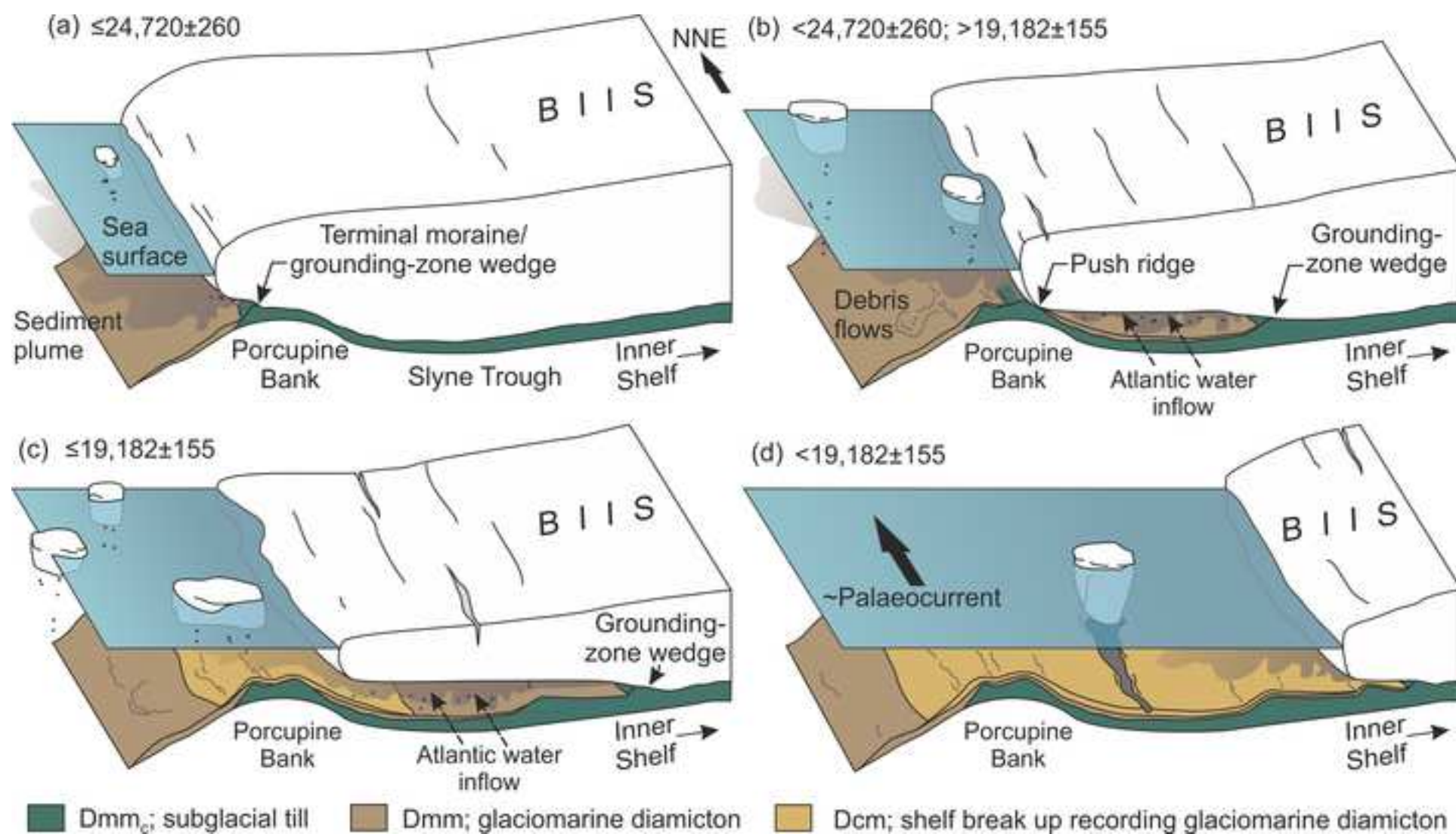


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