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### **Paper:**

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# 1 **Re-assessment of the age and depositional origin of the** 2 **Paviland Moraine, Gower, south Wales, UK**

3 **RICHARD A. SHAKESBY, JOHN F. HIEMSTRA, BERND KULESSA AND ADRIAN J.**  
4 **LUCKMAN**

5 Shakesby, R. A., Hiemstra, J. F., Kulesa, B. & Luckman, A. J.: Re-assessment of the age and  
6 depositional origin of the Paviland Moraine, Gower, south Wales, UK. The Bristol Channel,  
7 including onshore areas, is critical for reconstructing Pleistocene glacial limits in south-west  
8 Britain. Debate about the precise regional southern limits of Devensian (Oxygen Isotope Stage  
9 (OIS) 2) and Anglian (OIS 12) glaciations has recently been rekindled. The Paviland Moraine  
10 (Llanddewi Formation), Gower, south Wales is conventionally regarded as Anglian in age. Its ‘old’  
11 age has been based on reported highly weathered clasts, a subdued morphology and ‘field  
12 relationships’ to fossil beach sediments of now disputed age(s). Relatively little about its  
13 sedimentary characteristics has been previously published. This paper: (i) presents new  
14 sedimentological evidence including lithofacies analysis, XRF analysis and electrical resistivity  
15 tomography (ERT) of sediment cores and electrical resistivity of a tied 3D field grid; (ii) re-  
16 assesses the proposed ‘old’ age; (iii) suggests a likely depositional origin; and (iv) discusses  
17 implications for regional glacial dynamics and future research priorities.

18 The sediments comprise mostly dipping glacigenic diamict units containing mainly Welsh  
19 Coalfield erratics. The location and subdued moraine morphology are attributed to the hydrological  
20 influence of the underlying limestone, the local topography and ice sheet behaviour rather than to  
21 long-term degradation. Moraine formation is attributed mainly to sediment gravity flows that  
22 coalesced to produce an ice-frontal apron. Neither geochemical data nor clasts indicate prolonged  
23 subaerial weathering and *in-situ* moraine sediments are restricted to a limestone plateau above and  
24 inland of fossil beach sediments. We recommend rejecting the view that the moraine represents

25 the only recognised OIS 12 deposit in Wales and conclude that instead it marks the limit of  
26 relatively thin Last Glacial Maximum (LGM) ice in west Gower. This requires revision of the  
27 accepted view of a more restricted LGM limit in the area. We suggest that substrate hydrological  
28 conditions may be a more influential factor in moraine location and form than is currently  
29 acknowledged.

30

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36

37 Proximity to the Last Glacial Maximum (LGM; ~22 ka BP) limit and close association of well  
38 exposed glacial and non-glacial diamicts with fossiliferous beach and cave sediments  
39 largely explain why the Gower Peninsula, south Wales (Fig. 1A) has retained a prominent position  
40 in understanding British Quaternary chronology for nearly 200 years (e.g. Buckland 1823;  
41 Prestwich 1892; Charlesworth 1929; Mitchell 1960, 1972; Bowen 1970, 1999; Sutcliffe & Curren  
42 1984; Bowen & Sykes 1988; Hiemstra *et al.* 2009; Shakesby & Hiemstra 2015a). Most researchers  
43 have agreed that the peninsula was completely ice-covered on some occasion(s) before Oxygen  
44 Isotope Stage (OIS) 5e (~123-109 ka BP; Lisiecki & Raymo 2005) with only a partial cover at the  
45 LGM. Defining exactly where LGM ice terminated on the peninsula, however, has led to much  
46 difference of opinion and debate since the 1920s (e.g. Charlesworth 1929; Griffiths 1940; Mitchell  
47 1960, 1972; Bowen 1970, 1981a; Campbell 1984; Bowen *et al.* 1985; Bowen & Sykes 1988;  
48 Campbell & Bowen 1989; Clark *et al.* 2004; Evans *et al.* 2005; McCarroll & McCarroll 2015)  
49 because of the presumed lack of major LGM ice-front depositional landforms (end moraine,  
50 outwash plain or major outwash fan) other than minor, long destroyed sand and gravel mounds in  
51 south-east Gower (Charlesworth 1929) and a small exposure of probable outwash in west Gower  
52 (e.g. Strahan *et al.* 1907a; Campbell & Shakesby 2015). Despite different views about ice limits  
53 across Gower, it was widely agreed prior to research by Rijdsdijk (2000) and Hiemstra *et al.* (2009)  
54 that, from inspection of glacial sediments in extensive Quaternary exposures along the south  
55 coast, Rotherslade in south-east Gower (Fig. 1B) was the most westerly point reached by LGM  
56 ice.

57 Unlike south-east Gower, proposed glacial limits in west Gower have undergone  
58 considerable change. Before 1980, complete inundation by a pre-LGM ice sheet moving eastwards  
59 from the Irish Sea Basin (ISB) was favoured, with later LGM ice encroaching only a short distance

60 inland or not at all (e.g. Charlesworth 1929; Griffiths 1940; Bowen 1970). There was disagreement  
61 over the timing of complete inundation (see Campbell & Bowen 1989), but agreement about the  
62 influence of ice broadly from both the west (ISB) and the north (Welsh Coalfield), supported by  
63 distinctive erratics and heavy minerals (e.g. George 1933; Griffiths 1939; Campbell 1984).  
64 Apparently lacking a moraine, the LGM ice limit drawn across west Gower was mostly constrained  
65 by topographic obstacles (notably Cefn Bryn and Llanmadoc Hill; Figs 1B, 2), and supported by  
66 a  $^{36}\text{Cl}$  date on the capstone (Phillips *et al.* 1994; Bowen 1999) of the Neolithic burial chamber of  
67 Arthur's Stone long regarded as a more or less *in-situ* Devensian erratic (Owen 1964). LGM ice  
68 reached Broughton Bay in north-west Gower as indicated by glacitectorite containing wood,  
69 striated clasts, marine shells and foraminifera (e.g. Campbell *et al.* 1982; Campbell 1984;  
70 Campbell & Shakesby 1994, 2015; Shakesby *et al.* 2000).

71 The Paviland Moraine was first recognised in the early 1980s (Bowen 1981a, b, 1999,  
72 2005; Bowen *et al.* 1985) and initially regarded as LGM in age (Bowen 1981a), but later as an  
73 important Middle Pleistocene ice limit (or major stillstand) (e.g. Bowen & Sykes 1988; Bowen  
74 1999, 2005; Bowen *et al.* 2000). This importance is still current (e.g. Catt *et al.* 2006; Gibbard &  
75 Clark 2011; McMillan *et al.* 2011; Gibbard *et al.* 2017). Rijdsdijk (2000) and Hiemstra *et al.* (2009)  
76 raised the possibility of an LGM date but this was emphatically rejected by Bowen (2005).

77 We present new evidence from the Paviland Moraine comprising: (i) lithofacies analysis,  
78 XRF analysis, and electrical resistivity conducted on sediment from three cores up to ~11 m in  
79 length; (ii) a three-dimensional (3D) electrical resistivity tomography (ERT) grid survey carried  
80 out adjacent to the longest core; (iii) geochemistry of core sediments and selected glacial and  
81 non-glacial sediments from Gower and 'tills' from the Irish Sea Basin; and (iv) micro-XRF  
82 analysis of intact core and reference LGM-age glacial sediment from north-west Gower. Drawing

83 on this evidence together with that of palynomorphs reported by Riding (2007) and calcareous  
84 microfossils from selected core sedimentary units, we assess the likely age of the feature and the  
85 depositional environment and dynamics of the ice that formed it. Implications for improving our  
86 understanding of Pleistocene glacial chronology and LGM ice sheet behaviour on Gower are  
87 discussed together with future research priorities.

## 88 Background

### 89 *Paviland Moraine: previous research and description*

90 Until the late twentieth century, no sufficiently thick accumulation or suitable landform consisting  
91 of glacial sediment in west Gower possibly representing an end moraine was recognised. A  
92 southward extension of the LGM limit towards the south coast by Bowen (1981a) first drew  
93 attention to the possibility of more than a comparatively formless cover of glacial sediment in the  
94 area. Later, Bowen *et al.* (1985, p. 312) suggested that pre-LGM ice had produced what they then  
95 named as the Paviland Moraine (Fig. 3), and this was “proved by drilling in Gower” (though no  
96 supporting evidence was given in that paper). Possible minimum ages of OIS 8 (300-243 ka BP)  
97 or OIS 10 (374-337 ka BP) were suggested, though in later publications either OIS 6 (~191-123  
98 ka BP) or OIS 12 (~478-424 ka BP) was preferred (e.g. Campbell & Bowen 1989; Bowen 1999),  
99 because these ages “corresponded with enhanced [global] ice volume” (Bowen 2005, p. 159).  
100 Without direct dates on the moraine sediments or on underlying deposits, an ‘old’ (i.e. pre-LGM)  
101 age was based on three main lines of evidence: (i) proposed ‘field relationships’ of the moraine  
102 with respect to (now disputed; see McCarroll (2002)) amino-acid ratio- (AAR-) dated OISs 5e and  
103 7 (~243-191 ka BP) raised beach deposits lying distal to the moraine and said to contain indicator  
104 erratics from it (Bowen 2005); (ii) the reported highly weathered nature of moraine erratics; and

105 (iii) the subdued form of (part of) the moraine interpreted as indicating its “greatly degraded  
106 nature” (Bowen 2005, p. 149). More recently, there has been uncertainty concerning its end  
107 moraine status, Bowen *et al.* (2000, p. 61), for example, preferring that it represented a “stationary  
108 position during its retreat”, whereas Bowen (2005, p. 148) argued for it marking “the extent of the  
109 Llanddewi glaciation because cliff top plateaux and coastal valleys (slades) between Port Eynon  
110 and Rhosili are free of glacial or glaciofluvial deposits”, although George (1933) reported erratics  
111 in a number of coastal exposures. Gibbard & Clark (2011, p. 81) considered that the moraine  
112 sediments were “the only unequivocal Anglian-age unit” in south Wales representing “the margin  
113 of Anglian-age Welsh ice”, but added that this glaciation also “extended across the Bristol Channel  
114 as far as the northern coast of the English South-West Peninsula”.

115 The only published depictions of the moraine are small-scale sketch maps, which show it  
116 extending from near Rhossili eastwards towards Oxwich Green and then northwards towards Cefn  
117 Bryn (Fig. 4), though interest has mainly focused on the W-E aligned section. The eastern, N-S  
118 (hereafter referred to as the Oxwich Bay) section in contrast is in part heavily dissected, the present  
119 day small stream flowing in a steep-sided valley cut at least ~60 m into probable glacial  
120 sediments (e.g. Humpage *et al.* 2012), though confirmation of sediment characteristics is hindered  
121 by thick woodland vegetation and rare small exposures. The distal slope is steep, probably due to  
122 trimming by wave action during Holocene sea-level rise.

123 There has been some additional reporting of the sediments. First, Bowen *et al.* (2000, p.  
124 61) reported that they contained “characteristic erratics of Millstone Grit (Namurian) quartzites  
125 and conglomeratic quartzites”. Second, from four boreholes and accompanying electrical  
126 resistivity results, Smith *et al.* (2002) briefly reported 21.5 m of “deeply weathered sands and

127 gravel overlying red clay” on the crest and some 7.6 m of “dark blue clay” at Western Slade on  
128 the distal slope resting on limestone (Bowen 2005).

129         Bearing in mind the difficulties presented by the subtle form of much of the moraine and  
130 apparently widespread cover of glacial sediment but few inland exposures in west Gower, we  
131 present in Fig. 5 an approximate extent of the Paviland Moraine.

### 132 *Other possible moraines on the Gower Peninsula*

133 In addition to the Paviland Moraine, a few possible moraine remnants have been reported. First,  
134 on Welsh Moor in north-central Gower there is a near continuous, ~2.4-km long, narrow, slightly  
135 curved ridge (A in Fig. 2) clearly unrelated to bedrock structure. Interpreted as a possible  
136 recessional moraine by R.H. Tiddeman (in Strahan 1907b, p. 140-141), it was subsequently largely  
137 overlooked (e.g. Charlesworth 1929; George 1933; Mitchell 1960). According to Bowen (1970;  
138 fig. 9.1) it was an esker, and to Humpage *et al.* (2012) a glacialfluvial (i.e. sand and gravel) ridge,  
139 but small exposures reveal subangular and subrounded clasts in a sand-silt-clay matrix, thus  
140 making a waterlain origin unlikely. Second, two very indistinct features (B and C in Fig. 2) may  
141 also reflect a glacial retreat position. Third, Bowen (2005, fig. 10.1, p. 145) showed two glacial  
142 sediment accumulations in north Gower together with apparently matching mounds on the north  
143 side of the Loughor Estuary (Bowen 1980) implying E-W ice flow, but there is no supporting  
144 evidence for a moraine origin. Furthermore, this flow direction varies considerably from that  
145 implied by the Welsh Moor feature, a far more likely moraine, and clasts in glacialtonite at  
146 Broughton Bay show a consistent, virtual N-S rather than E-W strong preferred orientation  
147 (Campbell 1984; Campbell & Shakesby 1994). Fourth, Bowen (2005) listed an Oldwalls moraine  
148 fragment in north Gower (D in Fig. 2), forming part of his LGM ice limit.



## 149 Methods

### 150 *Sediment core retrieval and analysis*

151 In 2007, a British Geological Survey (BGS) drilling team obtained three sediment cores (WS-1,  
152 WS-2, and WS-3; Fig. 1D) on the distal slope of the Paviland Moraine upslope from Western Slade  
153 Farm using a Dando Terrier 2002 percussion drilling rig with a 117 mm barrel size. Some 30 core  
154 segments were retrieved in plastic liners. The WS-1 core, nearly 9 m long, was obtained from near  
155 the moraine crest, WS-2, ~11 m long, from a mid-slope ( $51^{\circ}33'15''$  N,  $4^{\circ}11'21''$  W), and WS-3,  
156 ~3 m long, from a footslope position (Fig. 1D). The cores were cut lengthwise, and one set  
157 described and analysed, using an approach similar to that of Eyles *et al.* (1983) and Evans & Benn  
158 (2004).

### 159 *Resistivity survey: field grid and core*

160 Electrical resistivity reflects mainly porosity, pore-water electrical conductivity and saturation,  
161 with clay and coarser sediment tending to give low and high values respectively. Chargeability, as  
162 measured by the induced polarisation (IP) method, commonly reflects pore-space and electrical  
163 properties of particle surfaces, and normalisation of this parameter by resistivity can be diagnostic  
164 of solid sediment constituent characteristics, with clay and relatively coarse sediment typically  
165 giving high and low values respectively (Reynolds 1997). A 3D electrical resistivity tomography  
166 (ERT) grid survey adjacent to core WS-2 (Fig. 1D) was complemented by jointly-acquired  
167 electrical resistivity chargeability data on a 2D profile along the southern grid margin. Direct  
168 measurements of values for the sedimentary facies were acquired from resistivity and IP logging  
169 of the core (see below).

170

171 Using an IRIS Syscal Pro 24-channel imaging system and a dipole-dipole electrode  
172 configuration (e.g. Reynolds 2011), 27 ERT profiles were acquired using an along-line 5-m  
173 electrode spacing. Profiles were set 10 m apart, except for profiles 1 to 6 (5 m spacing), to form a  
174 115 x 115 m 3D grid (Fig. 1D). ERT and IP data were acquired jointly along profile 27 using a  
175 Wenner- $\alpha$  electrode configuration (see Reynolds 2011).

176  
177 Core WS-2 was logged with a miniature resistivity array (Spalding 2010; cf. Sentenac *et*  
178 *al.* 2010), comprising stainless steel nails spaced 2 cm apart in Wenner- $\alpha$  configuration along a  
179 wooden rod consistent with a nominal depth of penetration of ~1 cm (e.g. Reynolds 2011). The  
180 array was connected to the manual terminals of the IRIS Syscal Pro instrument and multi-azimuth  
181 direct and reciprocal repeat measurements averaged to minimise any electrical anisotropy.

182  
183 *XRF geochemical analysis*  
184 Elemental chemistry of core sediments was examined by: (i) micro-XRF elemental mapping of  
185 two intact core samples and a reference sample; and (ii) XRF analysis of the <2 mm fractions of  
186 core and selected reference samples.

187 Micro-XRF elemental mapping was conducted using a Horiba XGT-7000 X-ray  
188 Fluorescence Microscope on core samples from two depths (7.73-7.79 m and 11.15-11.22 m)  
189 corresponding to subunits LF2b and LF3A2 in relatively clayey, generally clast-poor diamicts, and  
190 on LGM glaciectonite from Broughton Bay, north-west Gower (Table 1 and Fig. 1B).

191 To test whether moraine sediment shows pronounced post-depositional weathering as  
192 previously maintained (e.g. Bowen *et al.* 1985; Bowen & Sykes 1988; Bowen 2005), selected

193 weathering-sensitive ratios of elements according to Burek & Cubitt (1991) were calculated for  
194 core samples. Geochemistry was also used to help determine core sediment origins, whether they  
195 showed ISB or Welsh Coalfield affinities and to what extent pre-existing weathered material might  
196 be represented. To this end, in addition to eight WS-2 core samples, eight reference samples were  
197 analysed to determine their entire elemental content. The latter samples comprised: (i) two diverse  
198 diamicts from west Gower (a LGM glacitectorite with documented ISB material and a pre-LGM  
199 fine colluvial sediment considered to represent reworked soil with aeolian inputs); (ii) glacial, glacial,  
200 paraglacial and periglacial sediments from Rotherslade in south-east Gower, which are virtually  
201 only of Welsh Coalfield or local (limestone) slope origins; and (iii) classic ‘Irish Sea tills’ (see  
202 Table 1 for details of sites and references). Sample geochemistry was determined using a Rigaku  
203 NEX-CG EDXRF ([www.rigaku.com/products/xrf/nexcg](http://www.rigaku.com/products/xrf/nexcg)) following gentle air-drying of 5 g  
204 samples, which were ground, packed into 32-mm diameter cups and sealed with 4- $\mu$ m thick  
205 Prolene film.

206 Ward’s Hierarchical Agglomerative Clustering Method (Wessa 2012) was used to  
207 investigate similarities between core and reference sample geochemical data, both including and  
208 excluding elements recording ‘non-detected’ values. In addition, because calcareous microfossil  
209 content or fragments from underlying limestone bedrock might unduly influence cluster groupings,  
210 results were also obtained both including and excluding Ca values, but given little difference  
211 between the three dendrograms, only the one including all elements is presented.

## 212 Results

### 213 *Sediment core analysis*

214 In all 3 cores, there are stratified successions of pebbly sands, clays, and silty, sandy and clayey  
215 diamicts (Fig. 6). Some units are a few tens of cm, but most are 0.5-1.5 m thick. Contacts between  
216 units are often inclined (typically  $\sim 10\text{-}20^\circ$ ). Only in core WS-3, in a footslope position, are the  
217 beds (sub)horizontal. Three main lithofacies associations, LFA1 to LFA3, can be identified, with  
218 a full sequence only in core WS-2 (Table 2). Core WS-1 only contains LFA1, and core WS-3  
219 includes LFAs 1 and 2 but not LFA3. Contacts are relatively sharp between the three LFAs, but  
220 more gradational for units within them.

221  
222 Facies 1A is a yellowish-brown, homogeneous, loosely consolidated, massive, matrix-  
223 supported diamict (Dmm; codes after Eyles *et al.* 1983; Evans & Benn 2004). The matrix consists  
224 of silt to fine sand, with minor amounts of clay. Clast content is typically  $\sim 10\text{-}15\%$ . Clasts are  
225 granules or fine to medium, subangular to subrounded, predominantly sandstone (Old Red  
226 Sandstone and Coal Measures and quartzitic) pebbles. There is apparently no preferred orientation  
227 of clast a-axes, except for possible subhorizontal alignment in one 15-cm-thick, relatively clast-  
228 rich zone. Facies 1B consists of brownish-yellow to brown, interstratified silty to sandy diamicts  
229 Dmm/Dml and Dcm/Gm (1B1), silty diamicts Dmm/Dml and slightly gravelly massive silts Fm  
230 (1B2). Individual beds range in thickness from 10 cm to  $>1.5$  m. Facies 1B appears more compact  
231 than 1A. Clast content ranges from 7.5 to 40% (1B1) and from 2.5 to 15% (1B2). Clast size in 1B2  
232 is similar to that in facies 1A, but 1B1 units are coarser and also contain large pebbles. Irrespective  
233 of size, clasts are mostly subangular, with similar lithologies to facies 1A. Whilst mostly massive  
234 in character, both 1B1 and 1B2 show localised stratification with cm-scale (dis)continuous  
235 laminae, pods or lenses of sediment that is either coarser or finer than the surrounding matrix.  
236 Lamination is often highlighted by Fe/Mn staining. In places, facies 1B1 shows a preferred clast

237 a-axis orientation, commonly aligned with nearby (inclined) bed contacts. A few fractured clasts  
238 in 1B1/2 are seemingly strung out (at angles compatible with bed contacts and clast fabrics), and  
239 some circular structures of finer clasts are aligned with and wrapped around coarser clasts.

240

241         Facies 2A is a reddish-brown to brown, massive to stratified, apparently consolidated,  
242 matrix-supported fine silty to clayey diamict (Dmm/Dms). Clast content is ~7.5% throughout.  
243 Clasts are mostly subrounded, fine to medium, predominantly quartzite and sandstone pebbles.  
244 The stratification consists of inclined Mn-stained, cm-thick bands with a smaller clast content (2.5  
245 to 5%) and a medium sand matrix. Dispersed, mm-size 'black wood' and/or coal fragments (see  
246 Riding, 2007) occur throughout facies 2A. Facies 2B is a reddish-brown to brown, massive,  
247 apparently consolidated predominantly silty Dmm. Clast content is lower than in 2A (~2.5%),  
248 although dispersed clasts are coarser (up to several cm). Clast composition is similar to facies 2A,  
249 and mm-size 'black wood' and coal fragments are also present. Facies 2C is a reddish-brown to  
250 yellowish-brown, massive to laminated/stratified, matrix-supported, predominantly silty diamict  
251 (Dmm to Dms). Apart from colour and stratification in some parts, this facies is identical to facies  
252 2B, with some zones apparently almost clast-free. Stratification is very faint and subtle in the basal  
253 parts of the unit in core WS-2, but much more prominent in a virtually clast-free ~40-cm thick  
254 zone in core WS-3. The stratification here is caused by small variations in silt content in the  
255 generally distinctly clayey unit. Stratification is mostly discontinuous and lenticular with  
256 individual strata, boudins or laminae a few mm to a few cm thick. Interestingly, also in core WS-  
257 3, the lowermost 0.5 m of the core comprises sediment closely resembling facies 2A, albeit  
258 dominated by subangular limestone rather than subrounded sandstone clasts.

259

260 Facies 3A comprises two (3A1 and 3A2) units of greyish-brown, homogeneous and  
261 massive, stiff diamict (Dmm) to slightly gravelly, massive clay Fm. These identical units are  
262 separated by facies 3B. The matrix texture of 3A is distinctly clayey. Clast content is very low (~1  
263 to 2%) with granules and fine to medium pebbles (up to 1.5 cm). Some facies 3A1/2 zones lack  
264 particles over mm-size and are clayey. Angular quartzite fragments occur, but most clasts are  
265 subrounded Coal Measure sandstones. Facies 3B is a greyish-brown, massive, very stiff diamict  
266 Dmm to slightly gravelly, massive clay Fm. The matrix texture is clayey, but contains more fine  
267 silt than facies 3A1/2. Clast content is also marginally higher (~2.5 - 3.5%). Riding (2007)  
268 reported the presence of 'black wood'.

269

#### 270 *Electrical resistivity*

271

272 The 3D field grid survey (Fig. 7) shows two distinctive resistivity units: an upper unit with  
273 relatively high ( $> \sim 175 \Omega\text{m}$ ) and an underlying one with low ( $< 100 \Omega\text{m}$ ) resistivity. Low resistivity  
274 and high normalised chargeability values were found in the lower parts of the core. These parts  
275 are significantly more clayey than the upper parts, and *in-situ* measurements on the core sediments  
276 (Fig. 6; Spalding 2010) confirm low resistivity below  $\sim 7$  m depth. We are confident therefore that  
277 the 'low-resistivity' unit in the field survey corresponds to LFA2, and logically also LFA3 (below  
278 8.90 m), but there are some limitations with data reliability at such depths. The relatively high  
279 resistivity unit in the upper 7 m of core can be attributed to the silty and sandy diamicts of LFA1,  
280 with the high variability explained by the observed clast density and matrix texture variations in  
281 sub-units 1B1 and 1B2, which causes electrical anisotropy. The apparent gradual down-core

282 increase in resistivity in LFA1 (Fig. 6) does not seem to correspond to any observed  
283 sedimentological characteristics.

284

285 From the ERT results (Fig. 7), LFA2 and LFA3 appear to form most of the moraine  
286 subsurface. The geometry seems sheet-like without major thickness variations although the upper  
287 surface is undulating, but data uncertainties prevent firm conclusions. The resistivity unit  
288 representing the upper LFA1 facies, on the other hand, is comparatively thick near the northern  
289 edge of the grid (~7 m adjacent to core WS-2), then thins generally in a downslope direction to  
290 become absent in the central parts of the grid (Fig. 7).

291

#### 292 *XRF analysis*

293

294 As regards micro-XRF elemental mapping of intact facies 2B and 3A2 samples and a sample of  
295 Broughton Bay glacitectonite from north-west Gower (Table 1; Fig. 1), the main results are  
296 summarised with images shown only for Ca (Fig. 8). All three samples were dominated by Si, K,  
297 Rb and Ba, with traces of Ti and Zr, though in different concentrations and spatial distributions.  
298 Sr content was found to be relatively high in facies 2B, virtually absent from facies 3A2 and  
299 moderate for the glacitectonite, results that differ from those obtained from XRF analysis of the  
300 ground-down samples, which showed increasing Sr content in the order 2B, 3A2 and  
301 glacitectonite. The reasons for this difference are not clear, but possibly the content is of a patchy  
302 nature. Samples 2B and 3A2 revealed low 'background' Fe abundance and Fe concentrations  
303 covering ~5% of the mapped areas. The clearest differences related to Ca content (Fig. 8). The  
304 glacitectonite has sharply-bounded concentrations of Ca (~10% of the area) up to several mm in

305 diameter. They clearly represent previously reported marine shell fragments and foraminiferal  
306 tests (see Campbell & Shakesby 1994, 2015; Shakesby *et al.* 2000). In sample 2B, Ca forms fine  
307 specks (~1% of area) with diffuse outlines. In sample 3A2 there are slightly more abundant,  
308 slightly larger (up to 1.5 mm) specks with sharp boundaries. These are likely to be microfossil  
309 remnants since under incident-light microscopy, amongst unidentifiable calcareous fragments,  
310 *Syringopora* and a crinoid stem of Carboniferous age were discernible.

311

312 Table 3 gives weathering ratios comprising selected pairs of elements. Ratios for Ba:K and  
313 Ba:Sr show little change down-core. For Ti:Al, the only marked difference is the highest ratio in  
314 the uppermost sample. Sr:Ca and Ba:Ca increase overall down-core, which would suggest greater  
315 weathering at depth, while Fe:Mn is very variable and shows no systematic change with depth.

316

317 Cluster analysis of the chemical elements for core and reference samples (Table 1) shows  
318 that core samples 2A, 2B, 2C and 3B form a comparatively distinct group (Fig. 9). Samples 1B1  
319 and 1B2 are the next most similar and are linked to Criccieth brown ‘till’. Sample 1A and  
320 Rotherslade paraglacial diamict form a separate comparatively tight pairing. Rotherslade fan  
321 diamict shows some similarities to the latter two groups but the linkage is not strong. The  
322 remaining six samples show much weaker similarity scores. Amongst these, the remaining two  
323 ‘Irish Sea till’ samples (CricG and Aber) are the most similar, followed by Broughton Bay  
324 glacitectorite and sample 3A2, then Rotherslade periglacial diamict and lastly Worms Head  
325 colluvial sediment, which is the most dissimilar of all the samples.

326

327 Discussion



328 *Depositional origin of the moraine*

329

330 Although the three LFAs are clearly glacial, containing mostly far-travelled Welsh Coalfield  
331 debris, their architectures suggest that none represents *in-situ* till. In addition, apart from isolated  
332 flow-shear features, there are no systematic deformation structures indicative of subglacial  
333 shearing upon deposition (cf. Evans *et al.* 2006). Instead, we envisage the W-E moraine section  
334 building up by laminar sediment gravity flows emerging from points along a static ice front, the  
335 same proglacial process thought to have carried sediment to dry valley fans in south-east Gower  
336 at Rotherslade (Hiemstra *et al.* 2009) and Hunts Bay (Shakesby & Hiemstra 2015c). Such flows  
337 would have formed a relatively even moraine crestline and smooth distal slope where closely  
338 spaced, but an undulating crestline and irregular slope where wider apart (e.g. Krzyszkowski &  
339 Zieliński 2002). This origin is indicated by the following. First, the bedding in cores WS-1 and  
340 WS-2 (at near-crest and mid-slope positions, respectively) dips consistently at angles thought to  
341 match the palaeo-surface slope (presumed to be up to  $\sim 20^\circ$  locally). Second, according to the ER  
342 grid (Fig. 7), LFA1 forms lobes that thin downslope, as expected for debris flows starting at the  
343 crest. Although resistivity data reliability diminishes at depth, the LFA2 upper boundary appears  
344 relatively smooth, and therefore surface unevenness is accounted for mostly by the varying  
345 thickness of LFA1. Third, LFA1 comprises loosely consolidated, interstratified silty to sandy  
346 diamicts, silty gravels and gravelly silts. Matrices of the (sub-)units are texturally similar, with  
347 clast density variations defining crude sorting, mostly inversely graded, in facies 1B (see Fig. 7).  
348 This is common in muddy debris flow deposits (e.g. Naylor 1980), as are localised sediment  
349 deformation zones suggested by (i) variable preferred clast fabrics probably formed by basal shear  
350 in individual flows (see Menzies & Zaniewski 2003; Phillips 2006) together with isolated zones

351 of preferred unidirectional clast fabrics, (ii) discontinuous and lenticular laminations (or boudins),  
352 (iii) circular structures (turbates), and (iv) strung-out fractured clasts, similar to those produced  
353 when medium-sized clasts are broken up in experimental debris flows (Caballero *et al.* 2014).  
354 Fourth, the increasing concentration of large, angular, exclusively limestone clasts at the base (2.5-  
355 3 m) of core WS-3 prevented deeper drilling and indicated bedrock proximity. Here, in a footslope  
356 position, the ground surface slopes at a low angle matched by the subhorizontal dip in several  
357 sedimentary sub-units which, together with the shallow sediment depth, tally with sediment gravity  
358 flows thinning downslope. The distinctive form and texture of LFA1 compared with LFA2 and  
359 LFA3 have so far been stressed, but all three have structural similarities suggesting a process link.  
360 Thus the dipping, well defined, stratified bands formed of clast density variations in LFA1 and  
361 LFA2 and isolated zones of boudinage-type laminations in LFA2 are thought to reflect coalesced  
362 sediment gravity flows, and the micro-scale bands of coarse grain and granule concentrations in  
363 massive clayey units in LFA3 are the likely basal shear zones of these flows (cf. Hiemstra *et al.*  
364 2004).

365  
366 We suggest that the Paviland Moraine was formed at the limit of a thin ice lobe that moved  
367 S and SSW to occupy the shallow basin of west Gower. Thinness of the ice is supported by scarce  
368 or absent glacigenic sediment on hillslopes much above the highest points on the moraine  
369 (Hangman's Cross, 109 m a.s.l.; Kittle Top, 98 m a.s.l.) and weathered tors above ~100 m a.s.l. at  
370 the northern end of Rhossili Down (Campbell & Shakesby 2015). Confinement of the southern  
371 limit of the ice lobe to the peninsula is supported by: (i) glacigenic sediment in dry valley fans  
372 between Eastern Slade and Oxwich Point being relatively small in calibre, sparse and mostly mixed  
373 with limestone head, contrasting with fans immediately adjacent to the moraine where it occurs as

374 thick discrete lenses that include some coarse clasts and a mixed glaciogenic-limestone diamict; and  
375 (ii) recent bathymetric data showing no evidence of moraine development offshore from west  
376 Gower (Gibbard *et al.* 2017). We attribute the subdued morphology of the W-E section of the  
377 moraine in large part to the influence of an extensive network of sinks and passages in the  
378 underlying limestone (J. Cooper, pers. comm., 2016; cf. Krzyszkowski & Zieliński 2002) largely  
379 restricting meltwater availability at the ice front to that generating sediment gravity flows down  
380 the distal slope of the moraine. We consider that this enhanced subglacial drainage would also  
381 have influenced the position of the moraine together with the thinness of the ice limiting further  
382 extension of the ice front position. The uneven thickness of LFA1 (Fig. 7) is thought to represent  
383 separate individual sediment gravity flows, in contrast to the even thickness of the underlying  
384 lithofacies thought to represent merged flows. We consider that the well dissected nature of the  
385 Oxwich Bay section of the moraine can be attributed to its location on relatively impermeable  
386 Marros Group bedrock, which restricted substrate drainage and resulted in erosion of this section  
387 of the moraine by surface meltwater.

388

389         Certain differences in the moraine sedimentary units indicate possible differences in their  
390 origins and/or provenances. First, cluster analysis (Fig. 9) suggests that geochemically LF3A2  
391 most closely resembles the Broughton Bay glacitectonite and two ‘Irish Sea tills’ (Aberdaron and  
392 Criccieth grey ‘till’), whereas LFAs 1, 2 and 3B are most like the glaciogenic sediments from  
393 Rotherslade, east Gower (Table 1). Second, sand-size coal or ‘black wood’ fragments (Riding  
394 2007) are more abundant in LFA2B than in the underlying LF3A2. Third, calcareous microfossil  
395 fragments are more common in the fine sand fraction of LF3A2 than in LF3B. Fourth, according  
396 to Riding (2007), palynomorphs from LF2B contain mostly poorly-preserved Late Carboniferous

397 spores whereas LF3A2 has a more diverse assemblage that includes spores of Jurassic and  
398 probable Middle Eocene age and a single Cretaceous spore. The lack of diagnostic Quaternary  
399 palynomorphs in the Paviland Moraine sediments might be considered puzzling. Certainly, Hunt  
400 (1984) found such microfossils in six British glacial sediments and Riding (2004) found them  
401 in each of 17 glacial sediment samples from elsewhere in Wales. On the other hand, Riding *et*  
402 *al.* (2005) noted their rarity or absence in some glacial sediment samples elsewhere in Britain, so  
403 that their absence need not necessarily conflict with a glacial origin. Fifth, LF2B and LF3A2 differ  
404 in colour.

405         These differences in characteristics could reflect different provenances for LFAs 1, 2 and  
406 3B compared with LF3A1/2. Thus, an ISB influence for the latter might be interpreted from the  
407 more diverse palynomorph assemblage, the geochemical similarity to ‘Irish Sea tills’ and to  
408 Broughton Bay glacitectonite (Fig. 9), and the less common sand-size coal fragments. This would  
409 tally with occasional ISB erratic clasts found in west Gower (e.g. George 1933; Campbell 1984).  
410 Alternatively, LF3A1/2 could represent *in-situ* and reworked (see below) glacitectonite that  
411 incorporated post-Carboniferous debris retained in fissures and other surface depressions on the  
412 limestone plateau together with limestone fragments. Smith *et al.* (2002) argued that the plateau  
413 represents a sub-Mesozoic surface in explaining a Jurassic fossil found in basal head deposits near  
414 Horton. In addition, Triassic rocks crop out near Port Eynon and a large Liassic erratic was  
415 reportedly found in south-east Gower (though more than 100 years ago; Strahan *et al.* 1907b), so  
416 that post-Carboniferous spores could conceivably have been glacially entrained very locally rather  
417 than transported over any great distance. Interdigitation of LF3A1/2 and LF3B, with their implied  
418 contrasting provenances (both dominantly Welsh, but LF3A1/2 with additional ISB content), could  
419 be taken to indicate an interval of major fluctuations in the distribution of two ice masses in west

420 Gower, but a simpler explanation is that it reflects a phase of reworking of LF3A1 facies exposed  
421 upslope of core WS-2 following patchy deposition of LF3B.

#### 422 *Age of the Paviland Moraine*

423 We now review Bowen's (2005) arguments for the Paviland Moraine being 'old'. First, clasts in  
424 the cores show no greater weathering than observed in Devensian glacial deposits elsewhere  
425 in Gower. Indeed, the cores include many intact, lithologically varying, fine to medium pebbles  
426 with both angular and rounded edges together with *in-situ* fractured clasts. Observed sandstone  
427 pebbles with weathering rinds and disintegrated cores ('rottenstones'; George (1933)) also occur  
428 in Devensian glacial sediments in west Gower (e.g. Rhossili Bay; Campbell & Shakesby 2015).  
429 In addition, weathering ratios (Table 3) indicate no systematic down-core change that would  
430 indicate long-term post-depositional subaerial weathering (cf. Bowen 2005, fig. 10.4).

431 Second, moraine sediments have indeed not been found overlying erratic-bearing  
432 interglacial fossil beach deposits, as Bowen (2005) considered important in arguing for a pre-  
433 Devensian age, but: (i) the moraine is restricted to the limestone plateau well above any fossil  
434 beach fragments, so that lack of superposition is unsurprising; and (ii) moraine clast lithologies  
435 essentially differ little from those in glacial till of accepted Devensian age in Broughton Bay,  
436 where superposition has been observed (Campbell *et al.* 1982; Campbell 1984). At both sites,  
437 Welsh Coalfield lithologies dominate: these and more exotic lithologies with a west or north-west  
438 provenance have been reported from fossil beach and glacial sediments both in coastal  
439 sequences distal to the moraine and, more rarely, farther east in Gower (e.g. George 1933; Bowen  
440 1971).

441 Third, as argued in the previous section, the subdued morphology of the W-E aligned  
442 moraine section more likely reflects the mode of moraine accumulation rather than indicating  
443 prolonged post-depositional sub-aerial degradation and therefore great age. The contrasting  
444 heavily-dissected Oxwich Bay section shows that in any case a subdued morphology descriptor  
445 only applies to part of the moraine.

#### 446 *Extent of the LGM ice sheet on Gower*

447 Like Rijdsijk (2000) and Hiemstra *et al.* (2009), we reject Bowen's (e.g. 1970, 1999, 2005) widely  
448 accepted view that glacial sediments in truncated dry valley fans at Rotherslade and to the east  
449 on Gower include *in-situ* glacial diamicts, and therefore lie inside the LGM margin while those to  
450 the west (including those distal to the W-E section of the Paviland Moraine) represent pre-  
451 Devensian glacial sediment redistributed by alluvial and colluvial action during the Devensian.  
452 Instead, we argue that ice-contact sediment gravity flows, like those envisaged for forming the W-  
453 E section of the Paviland Moraine and contributing to adjacent coastal fans, appear to be a more  
454 plausible origin for glacial sediment found elsewhere in other dry valley fans. This origin  
455 explains better the often sharp basal contact of exclusively glacial sediment with limestone  
456 head together with mixtures of these diamicts in a number of south coast dry valley fan sequences.  
457 Supporting this origin are: (i) the mixed boulder-to-clay size, often undiluted, glacial diamict  
458 that would otherwise have to have been transported by periglacial processes sometimes within  
459 very small catchments over very low-angled slopes; and (ii) the similar stratigraphic characteristics  
460 and topographic relations of many south coast fans containing discrete glacial diamict.

461 An alternative suggestion of how glacial sediments may have reached coastal exposures  
462 was outlined by McCarroll & McCarroll (2015). They pointed out that applying an ice-contact

463 sediment flow origin to all south Gower sediment exposures requires an unrealistically precise  
464 configuration of the ice-sheet margin to enable delivery of glacial debris to all coastal sediment  
465 fans, some of which have very short dry valley or cliff-notch heads. They argue instead for  
466 paraglacial remobilisation of glacial sediments following variable deposition of a 'sprinkling'  
467 of erratics by LGM ice that inundated the whole peninsula and effected little erosion. Like the  
468 periglacial remobilisation origin, generation of sufficient energy within very small, low-angled  
469 catchments to transport sizeable quantities of glacial diamict containing large-calibre debris,  
470 much of which is undiluted, to dry valley heads is also problematic with this origin. Moreover,  
471 there are reasons to reject it for both the west and the extreme south-east of Gower. As regards  
472 west Gower: (i) assuming an LGM age for the Paviland Moraine, there was clearly substantial  
473 rather than limited glacial deposition over a wide area; and (ii) glacial debris is plentiful in  
474 sediment fans adjacent to the moraine (e.g. Eastern Slade; Campbell & Bowen 1989), but at most  
475 sparse and mixed with limestone debris at any distance from it, even for dry valleys that penetrate  
476 relatively far into the plateau (e.g. south of Oxwich Green; see Figs 1B and 2). In south-east  
477 Gower, at Rotherslade, there is strong evidence for a mainly glacial and paraglacial sediment  
478 gravity flow origin to explain much of its considerable accumulation of glacial sediment,  
479 leading Hiemstra *et al.* (2009) to conclude that it was produced by an LGM ice lobe that did not  
480 extend westwards from Swansea Bay onto the south-east part of the peninsula.

481         If our explanation for glacial sediments in dry valley successions in west Gower and a  
482 previous similar explanation for them at Rotherslade in south-east Gower (Hiemstra *et al.* 2009)  
483 are correct, the 'problem' dry valley - sediment fan associations lie between these two areas on the  
484 south coast. A third ice lobe may have moved S-SSE in this section for which there is some support  
485 in: (i) the alignment of the Welsh Moor recessional moraine (Fig. 2) suggesting such an ice flow

486 direction and not the conventionally accepted south-westerly direction (cf. Patton *et al.* 2013); (ii)  
487 glacial sediment commonly found virtually at all heights unlike its largely limited vertical  
488 extent in west Gower; and (iii) the rarity of ISB erratics east of Oxwich Bay compared with their  
489 ‘relative abundance’ in west Gower (George 1933), implying different provenances. There is no  
490 obvious morainic development near the coast, however, despite a limestone substrate. The search  
491 for a plausible origin for the delivery of similar, undiluted, unsorted glacial diamicts to coastal  
492 sedimentary fans needs to continue. At present, however, our ‘proglacial’ sediment gravity flow  
493 origin seems to offer the best working hypothesis.

#### 494 *Future research*

495 The following research gaps can be highlighted. First, thorough, accurate (re)mapping and  
496 analysis of key glacial sediments on inland Gower as well as at the coast are overdue. The  
497 high-resolution DEM image (Fig. 2) could provide a useful springboard to new discoveries.

498 Second, the extensive limestone cave systems in west Gower could provide new  
499 opportunities for examining and dating the glacial sediments (cf. Farrant *et al.* 2014).

500 Third, recent bathymetric data (Gibbard *et al.* 2017) reveal the probable LGM end moraine  
501 to ice filling Swansea Bay, supporting previous sea-floor sediment investigations (Blackley 1978;  
502 Culver & Bull 1979), recent views about LGM ice encroachment onto south-east Gower (Hiemstra  
503 *et al.* 2009) and ice cap modelling (Patton *et al.* 2013). The extent, sedimentary characteristics,  
504 depositional origins and ages of these and other possible sea-floor glacial sediments and their  
505 relation to onshore sediments are needed.

506 Fourth, reliable calibrated- or numerical-age dates for glacial diamicts and associated  
507 sediments are lacking on Gower. The altitude of Arthur’s Stone burial chamber (147 m a.s.l.) is  
508 substantially more than most glacial debris in west Gower, which raises doubt about the validity



509 of the LGM  $^{36}\text{Cl}$  date obtained from its capstone (Phillips *et al.* 1994; Bowen 1999), With few  
510 new opportunities of this sort for numerical-age dating of glacial sediments, systematic application  
511 of recent promising advances in AAR analysis (intra-crystalline protein composition; Penkman *et*  
512 *al.* 2008; Demarchi *et al.* 2013a, b; Tomiak *et al.* 2013) to critical Gower fossil beach remnants  
513 would re-establish a reliable AAR-based chronological framework to constrain the maximum ages  
514 of overlying glaciogenic-bearing sedimentary sequences.

515 Fifth, the provenance of glacial sediments has relied heavily on small numbers of often  
516 poorly documented erratics found more than a century ago. Replicating these finds has proved  
517 difficult (e.g. Henry 1984; Waters & Lawrence 1987; Wilson *et al.* 1990; Bevins & Donnelly  
518 1992). A thorough assessment of the reliability of all erratic material is needed and the possibility  
519 of non-glacial transport origins considered (cf. Jenkins *et al.* 1985) to ensure robust interpretations.

520

## 521 **Conclusions**

522 Over the last 30 years, the Paviland Moraine (Llanddewi Formation) in west Gower, south Wales  
523 has been given the status of a stratotype for a Middle Pleistocene glaciation in south-west Britain.  
524 We dispute this interpretation and conclude the following about its morphology, stratigraphy,  
525 sedimentary characteristics, likely age and mode of deposition.

526

- 527 • Examination of up to ~11 m of moraine sediment cores and resistivity shows dipping beds  
528 of sands, clays and silty, sandy and clayey diamicts dominated by subangular and  
529 subrounded clasts originating from the Welsh Coalfield to the north. The dips are thought  
530 to reflect an origin by sediment gravity flows down the moraine distal slope. Less  
531 pronounced banding and laminations in the more clay-rich lower parts are attributed to

532 laminar slope flows. Some of these flows reached adjacent dry valley heads and cliff  
533 notches along the seaward margins of the limestone plateau on which the moraine lies,  
534 where they interdigitated or mixed with contemporaneous, locally-derived limestone head.  
535 The Oxwich Bay moraine section, resting on relatively impermeable bedrock, is  
536 contrastingly heavily dissected by surface meltwater.

537 • We reject a Middle Pleistocene age for the moraine, previously inferred from: (i) the  
538 subdued morphology of its W-E aligned section, which we attribute instead to its mode of  
539 deposition; (ii) its supposed highly weathered nature, which is not supported by  
540 observations and geochemistry of the core sediments; and (iii) its lack of superposition on  
541 fossil beach sediments of now disputed age(s), which we attribute to moraine deposition  
542 being restricted to the limestone plateau inland of and beyond the height range of these  
543 sediments. The current stratotype status of the Llanddewi Formation should thus be  
544 abandoned and a far more likely Devensian (OIS 2) date accepted.

545 • A Devensian age for the Paviland Moraine requires revision of currently accepted views  
546 of the maximum extent and nature of LGM ice on Gower. Its relatively large size and the  
547 scarcity of glacial debris much beyond its vertical and spatial extent suggest that the  
548 moraine marks the limit of relatively thin ice in west Gower. Previous research indicated  
549 that an ice lobe occupied Swansea Bay but did not encroach onto south-east Gower. The  
550 alignment of a probable recessional moraine in north-central Gower indicates a S-SSE-  
551 flowing ice lobe may have affected central Gower.

552 • We suggest that moraine location and form were influenced not only by ice sheet behaviour  
553 and topography but also by substrate hydrological conditions, which may be more  
554 influential than is currently acknowledged.

555

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565

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773 **Figure captions**

774 Fig. 1 A. Location of the Gower Peninsula in Great Britain. B. Locations of places and features  
775 on the peninsula mentioned in the text. C. Simplified geology. D. Locations of cores and electrical  
776 resistivity grid on the Paviland Moraine near Western Slade in west Gower (site identified by open  
777 square in B).

778 Fig. 2 Digital Elevation Map (DEM) of the Gower Peninsula based on LIDAR imagery. Letters  
779 refer to possible moraine fragments in addition to the Paviland Moraine (A = Welsh Moor; B and  
780 C = indistinct, possible moraine fragments near Fairwood and Three Crosses; D = Oldwalls). See  
781 text for explanation. © Environment Agency.

782 Fig. 3 Cross-sectional view of the W-E part of the Paviland Moraine looking east. Note the subtle  
783 morphology of the moraine (crest arrowed) at this point and its position on the limestone plateau.  
784 (Photo: J. Cooper).

785 Fig. 4 Published representations of the Paviland Moraine using the symbols and detail of the  
786 originals. A. Bowen (1981a), where the moraine is depicted as part of the last (Devensian) glacial  
787 limit. B. Bowen *et al.* (1985), where for the first time it is shown as a separate pre-Devensian limit.  
788 C. Bowen and Sykes (1988). D. Campbell and Bowen (1989). E. Bowen (2005).

789 Fig. 5 The dashed line indicates the estimated extent of the Paviland Moraine in west Gower  
790 based on field observation and the Digital Elevation Map shown in Fig. 2.

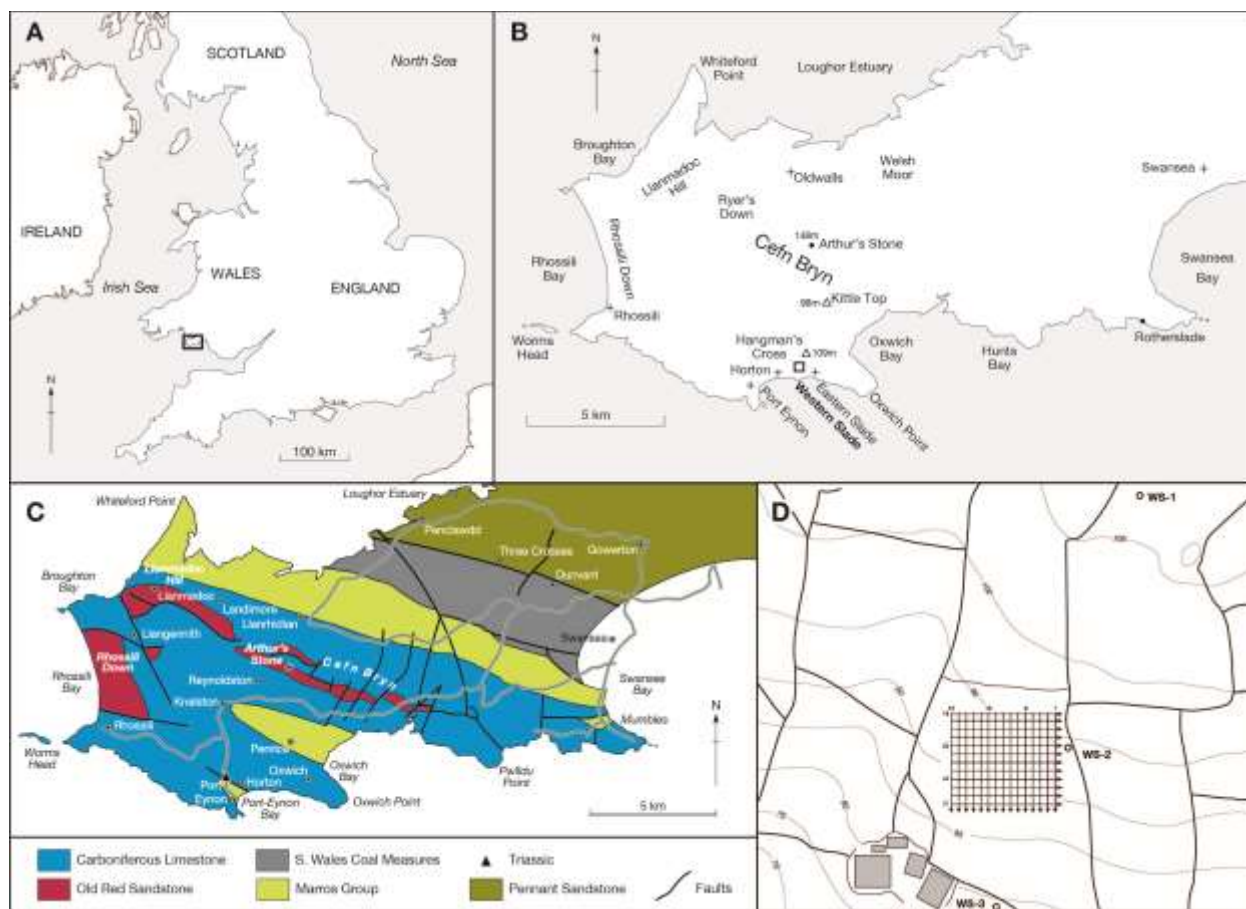
791 Fig. 6 Left: graphic log of core WS-2, Western Slade. Right: electrical resistivity and  
792 chargeability of core WS-2 (after Spalding (2010)). Error bars on electrical resistivity and  
793 chargeability graphs represent standard deviations of the repeat measurements.

794 Fig. 7 3D representations of the electrical resistivity measurements carried out on the grid shown  
795 in Fig. 1D. The upper diagram shows profile 1, adjacent to the core location, looking west. The  
796 middle diagram shows the configuration of the high resistivity unit and the lower one the low  
797 resistivity unit: both are viewed looking north-west. Taking the elevation differences of individual  
798 electrodes into account, the 27 dipole-dipole ER profiles were inverted using the tomography code  
799 DCIP3D, while the joint ER and IP data for profile 27 were inverted using the code DCIP2D.

800 Fig. 8 Micro-XRF elemental maps of Ca content for intact samples of subunits from LF2B (A),  
801 LF3A2 (B) in core WS-2 and Broughton Bay glacitectorite (C) from north-west Gower. A 100  
802  $\mu\text{m}$  X-ray source beam setting was used to obtain the 16 x 16 mm images.

803 Fig. 9 Cluster dendrogram for eight core and eight reference samples of glacial and non-  
804 glacial sediments from Gower and the Irish Sea Basin. The key to the abbreviated sample  
805 labels together with sediment descriptions and references are given in Table 1.

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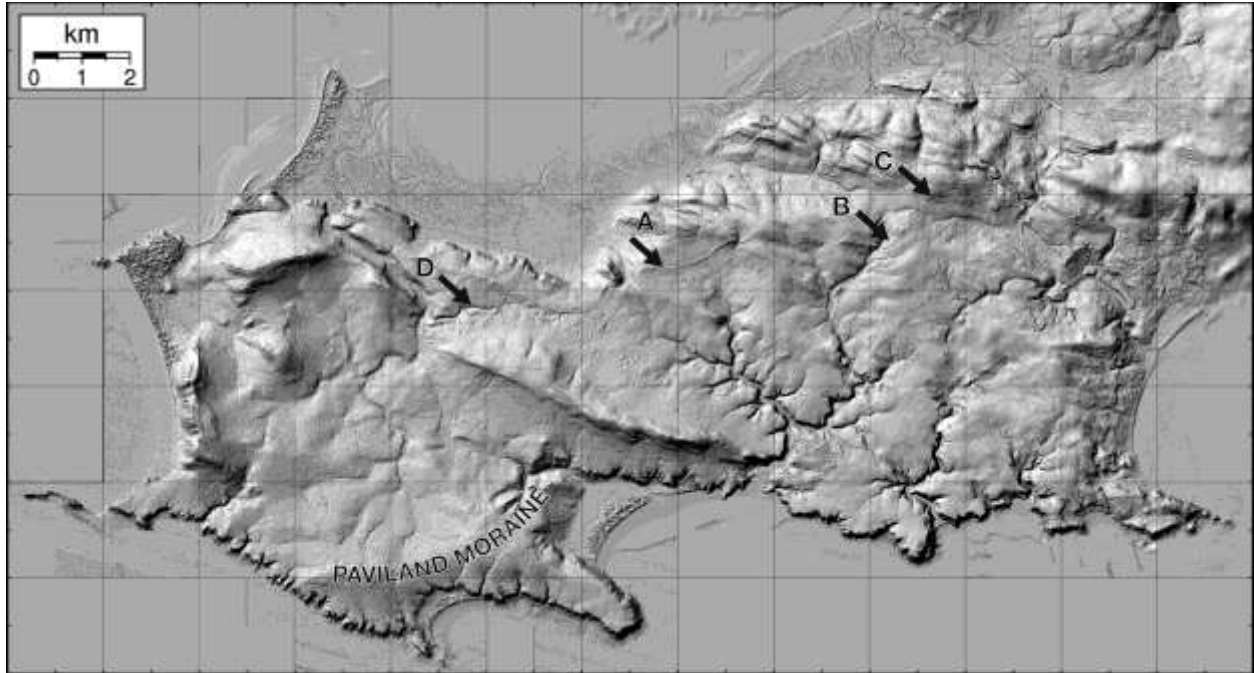


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Fig. 1



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Fig. 2



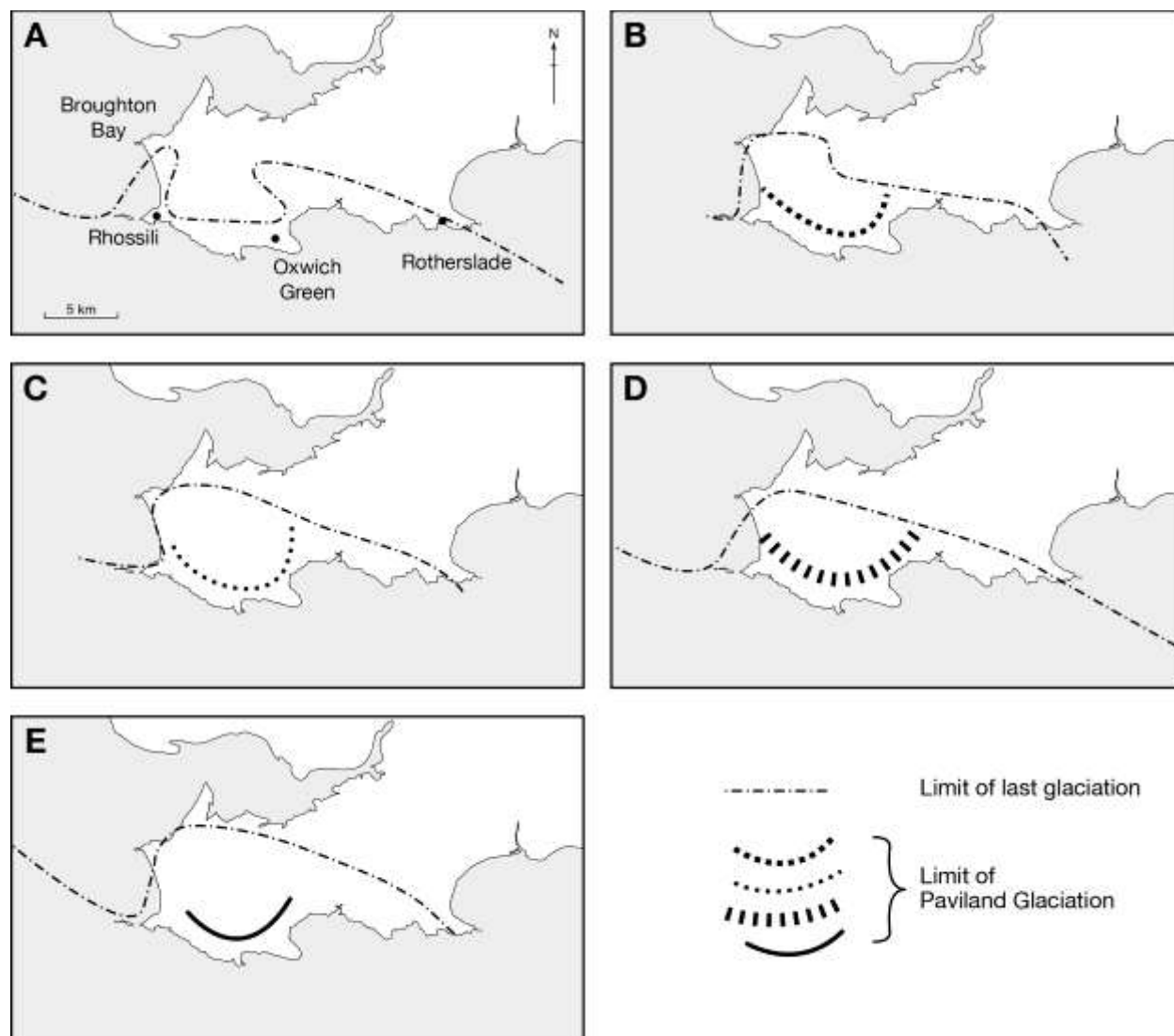


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Fig. 3

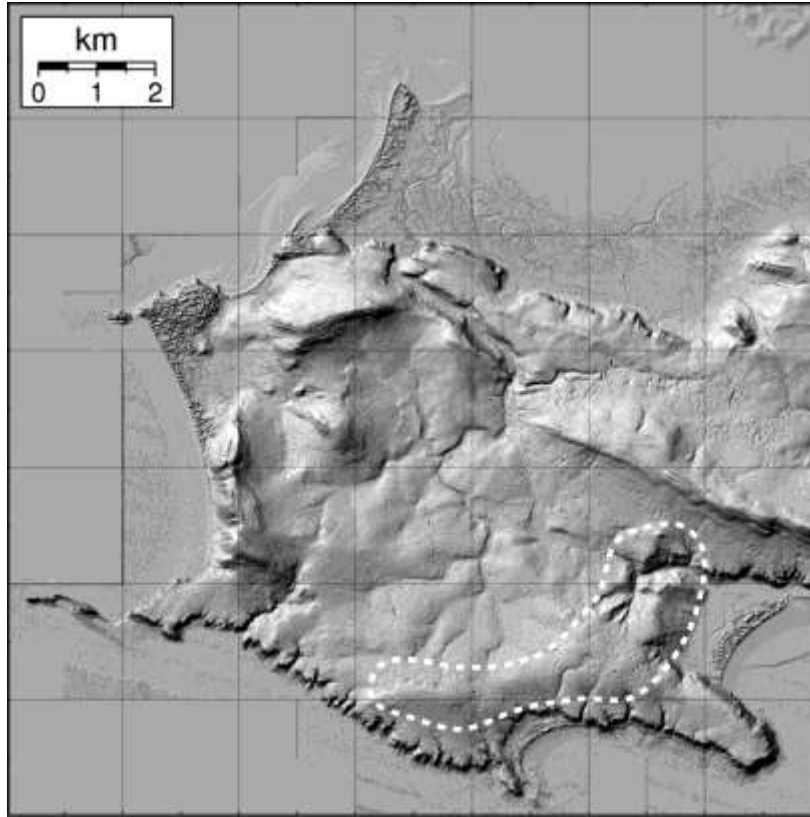


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Fig. 4

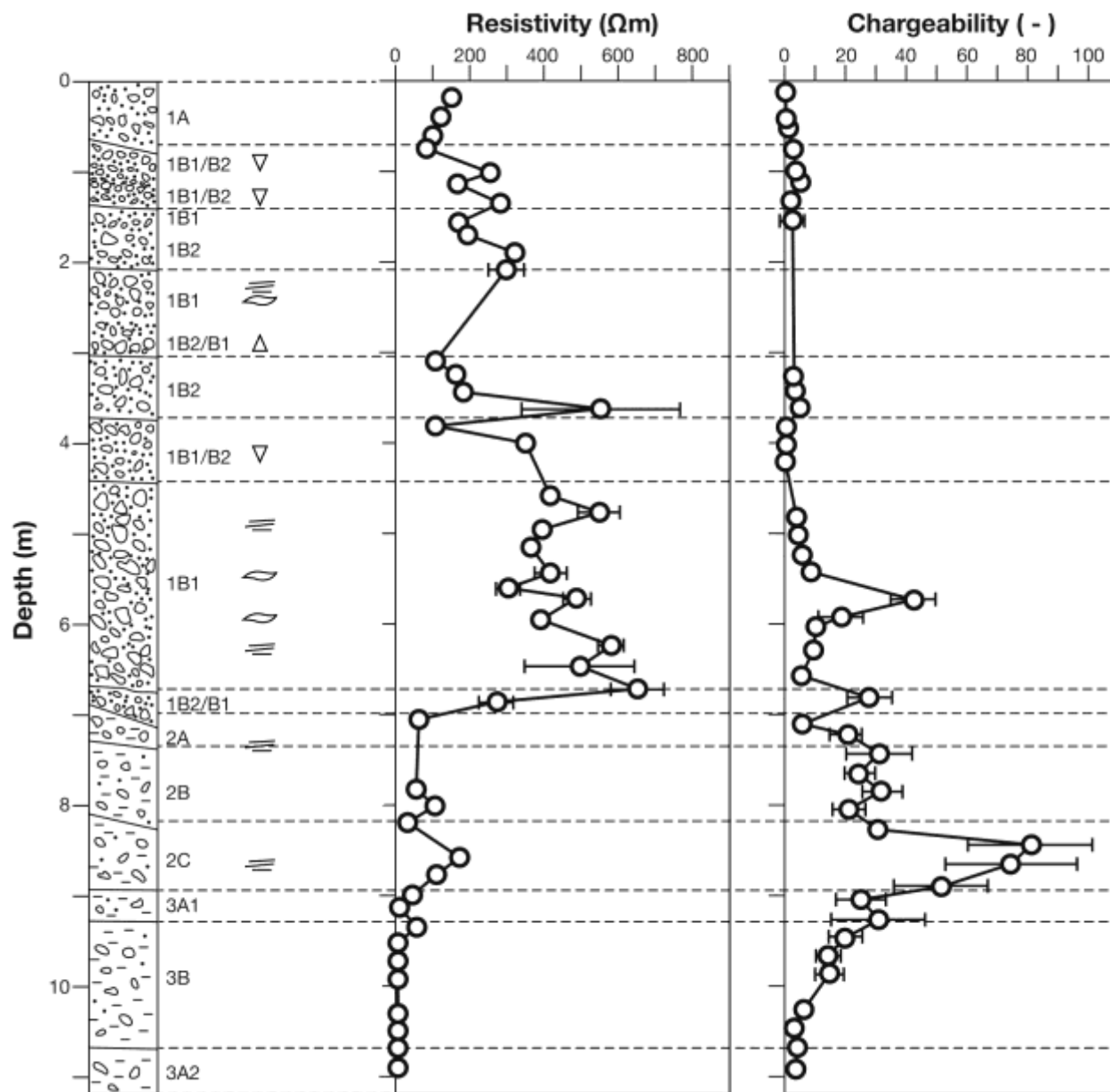


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Fig. 5

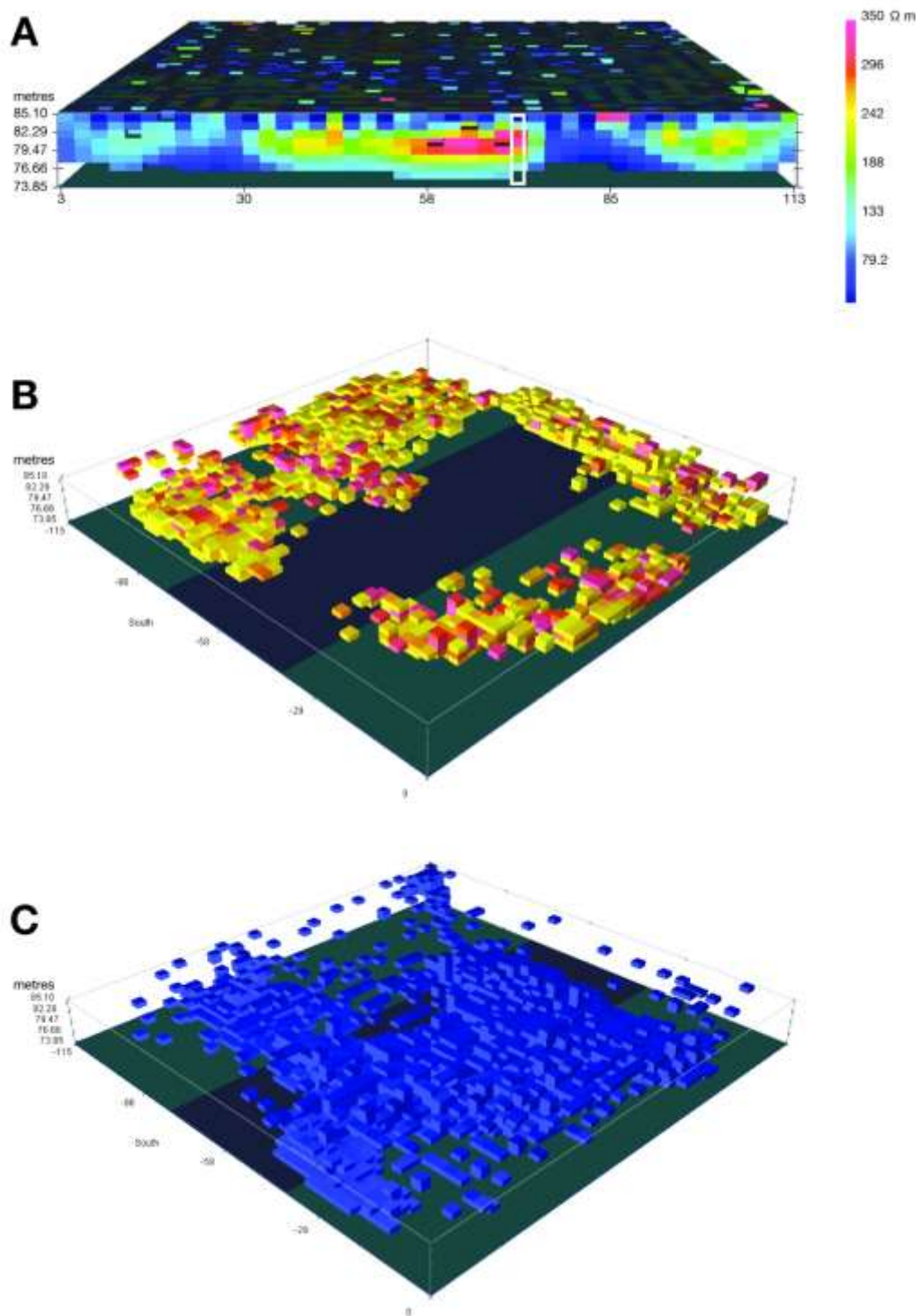


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Fig. 6



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Fig. 7

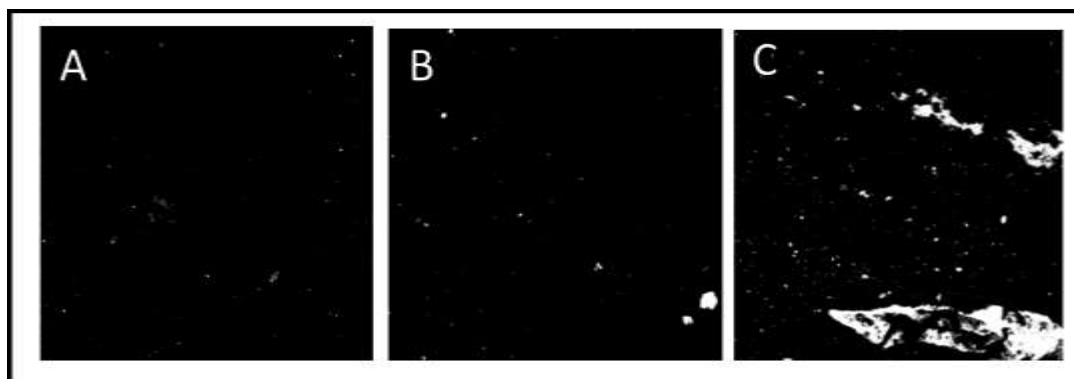


Fig. 8

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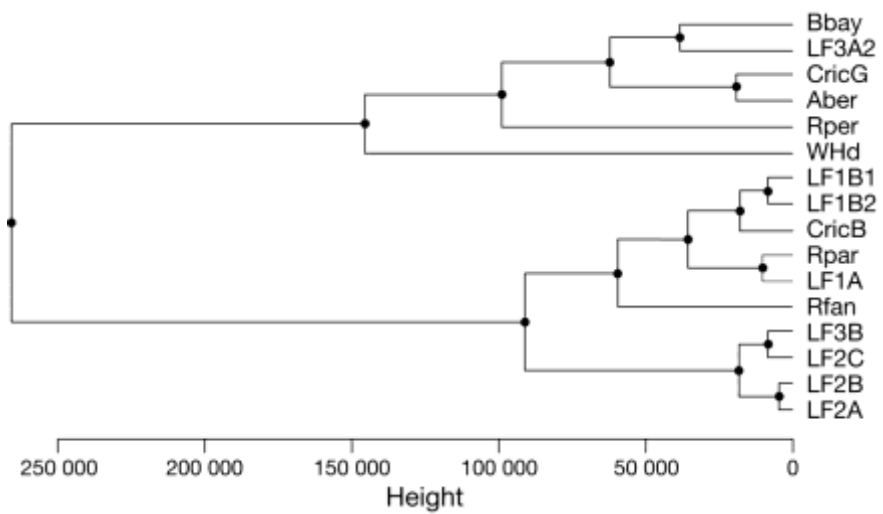


Fig. 9

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840 *Table 1.* Locations, codes, sediment types, suggested origins and publications relating to the eight XRF samples selected for  
 841 core samples. See Fig. 9.

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Location	Identification code	Sediment type	Suggested origin	Reference(s)
Worms Head, Gower	WHd	Clay-rich sediment	Colluvium with windblown marine sand	Ball (1960); Campbell & Bowen (1989)
Broughton Bay, NW Gower	BBay	Mixed lithology diamict containing wood, marine shells and foraminiferal tests	Glacitectonite	Campbell & Shakesby (1994, 2015); Shakesby <i>et al.</i> (2000)
Rotherslade, E Gower	Rper	Limestone-dominant diamict (unit B1)	Locally-derived periglacial slope deposit	Hiemstra <i>et al.</i> (2009)
Rotherslade, E Gower	Rfan	Mixed lithology diamict (unit C1/C6)	Proglacial outwash	Hiemstra <i>et al.</i> (2009)
Rotherslade, E Gower	Rpar	Mixed lithology diamict (unit D)	Paraglacial mass flow	Hiemstra <i>et al.</i> (2009)
Aberdaron, NW Wales	Aber	'Irish Sea till'	Subglacial	McCarroll (1992)
Criccieth, N Wales	CricG	'Irish Sea till' (grey)	Subglacial	Boulton (1977)
Criccieth, N Wales	CricB	'Irish Sea till' (brown)	Possible weathered version of CricG	Boulton (1977)

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Table 2. Succession of sedimentary units and lithofacies associations in core WS-2. For sediment descriptions, see text. See

Depth (cm)	Unit (facies)	Lithofacies association	Selected sedimentary characteristics	
0-74	1A	LFA1		
74-113	1B1→1B2	LFA1		
113-160	1B1→1B2	LFA1		
160-167	1B1	LFA1	<ul style="list-style-type: none"> <li>• yellow-brown, predominantly sandy Dmm/Dml/Dms</li> <li>• clast content: 2.5 - 40% - beds/lenses of Dcm</li> <li>• loosely compacted</li> <li>• mainly subrounded sandstone clasts</li> <li>• alternating beds defined by variable clast de</li> </ul>	
167-204	1B2	LFA1		
204-260	1B1	LFA1		
260-295	1B2→1B1	LFA1		
295-370	1B2	LFA1		
370-442	1B1→1B2	LFA1		
442-675	1B1	LFA1		
675-700	1B2→1B1	LFA1		
700-730	2A	LFA2		<ul style="list-style-type: none"> <li>• red-brown, clayey to silty Dmm/Dml/Dms</li> <li>• clast content: 2.5 - 7.5%</li> <li>• normally compacted</li> <li>• mainly subrounded sandstone clasts; locally</li> <li>• locally discontinuous mm-cm scale stratific</li> <li>• (boudins)</li> </ul>
730-816	2B	LFA2		
816-890	2C	LFA2		
890-925	3A1	LFA3	<ul style="list-style-type: none"> <li>• grey-brown, clayey to fine silty Dmm to (gr</li> <li>• clast content: 1 - 3.5%</li> <li>• highly compacted</li> <li>• mainly subrounded sandstone clasts</li> <li>• dispersed clasts in ill-defined, inclined band</li> <li>• parallel a-axis fabrics</li> </ul>	
925-1065	3B	LFA3		
1065-1115	3A2	LFA3		

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850 *Table 3.* Ratios for pairs of elements from core WS-2 samples. Ratios are selected for their sensitivity to weathering. Exp  
851 ratio with greater weathering are indicated. See Burek & Cubitt (1991). Asterisk denotes expected change with greater we

Sample	Depth (m)	Ba:K	Ti:Al	Fe:Mn	Sr:Ca	Ba:Ca	Ba:Sr
		Increase*	Increase*	Decrease*	Increase*	Increase*	Increase*
LF1A	0.3	0.016	0.059	19.15	0.023	0.104	4.52
LF1B2	0.85	0.014	0.050	59.10	0.029	0.132	4.63
LF1B1	1.1	0.015	0.053	60.06	0.033	0.148	4.52
LF2A	7.2	0.014	0.047	159.43	0.063	0.303	4.81
LF2B	7.7	0.014	0.047	74.70	0.050	0.261	5.18
LF2C	8.85	0.013	0.045	116.67	0.040	0.216	5.37
LF3B	10.55	0.013	0.045	129.22	0.036	0.201	5.56
LF3A	11.05	0.016	0.048	44.94	0.050	0.203	4.04

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