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

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

The sediments comprise mostly dipping glacigenic diamict units containing mainly Welsh Coalfield erratics. The location and subdued moraine morphology are attributed to the hydrological influence of the underlying limestone, the local topography and ice sheet behaviour rather than to long-term degradation. Moraine formation is attributed mainly to sediment gravity flows that coalesced to produce an ice-frontal apron. Neither geochemical data nor clasts indicate prolonged subaerial weathering and *in-situ* moraine sediments are restricted to a limestone plateau above and inland of fossil beach sediments. We recommend rejecting the view that the moraine represents the only recognised OIS 12 deposit in Wales and conclude that instead it marks the limit of relatively thin Last Glacial Maximum (LGM) ice in west Gower. This requires revision of the accepted view of a more restricted LGM limit in the area. We suggest that substrate hydrological conditions may be a more influential factor in moraine location and form than is currently acknowledged.

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

Unlike south-east Gower, proposed glacial limits in west Gower have undergone considerable change. Before 1980, complete inundation by a pre-LGM ice sheet moving eastwards from the Irish Sea Basin (ISB) was favoured, with later LGM ice encroaching only a short distance inland or not at all (e.g. Charlesworth 1929; Griffiths 1940; Bowen 1970). There was disagreement over the timing of complete inundation (see Campbell & Bowen 1989), but agreement about the influence of ice broadly from both the west (ISB) and the north (Welsh Coalfield), supported by distinctive erratics and heavy minerals (e.g. George 1933; Griffiths 1939; Campbell 1984). Apparently lacking a moraine, the LGM ice limit drawn across west Gower was mostly constrained by topographic obstacles (notably Cefn Bryn and Llanmadoc Hill; Figs 1B, 2), and supported by a ^{36}Cl date on the capstone (Phillips *et al.* 1994; Bowen 1999) of the Neolithic burial chamber of Arthur's Stone long regarded as a more or less *in-situ* Devensian erratic (Owen 1964). LGM ice reached Broughton Bay in north-west Gower as indicated by glacitectonite containing wood, striated clasts, marine shells and foraminifera (e.g. Campbell *et al*. 1982; Campbell 1984; Campbell & Shakesby 1994, 2015; Shakesby *et al.* 2000).

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

We present new evidence from the Paviland Moraine comprising: (i) lithofacies analysis, XRF analysis, and electrical resistivity conducted on sediment from three cores up to ~11 m in length; (ii) a three-dimensional (3D) electrical resistivity tomography (ERT) grid survey carried out adjacent to the longest core; (iii) geochemistry of core sediments and selected glacigenic and non-glacigenic sediments from Gower and 'tills' from the Irish Sea Basin; and (iv) micro-XRF analysis of intact core and reference LGM-age glacial sediment from north-west Gower. Drawing on this evidence together with that of palynomorphs reported by Riding (2007) and calcareous microfossils from selected core sedimentary units, we assess the likely age of the feature and the depositional environment and dynamics of the ice that formed it. Implications for improving our understanding of Pleistocene glacial chronology and LGM ice sheet behaviour on Gower are discussed together with future research priorities.

Background

Paviland Moraine: previous research and description

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

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

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

There has been some additional reporting of the sediments. First, Bowen *et al.* (2000, p. 61) reported that they contained "characteristic erratics of Millstone Grit (Namurian) quartzites and conglomeratic quartzites". Second, from four boreholes and accompanying electrical resistivity results, Smith *et al.* (2002) briefly reported 21.5 m of "deeply weathered sands and gravel overlying red clay" on the crest and some 7.6 m of "dark blue clay" at Western Slade on the distal slope resting on limestone (Bowen 2005).

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

Other possible moraines on the Gower Peninsula

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

Methods

Sediment core retrieval and analysis

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

Resistivity survey: field grid and core

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

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

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

XRF geochemical analysis

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

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

To test whether moraine sediment shows pronounced post-depositional weathering as previously maintained (e.g. Bowen *et al.* 1985; Bowen & Sykes 1988; Bowen 2005), selected weathering-sensitive ratios of elements according to Burek & Cubitt (1991) were calculated for core samples. Geochemistry was also used to help determine core sediment origins, whether they showed ISB or Welsh Coalfield affinities and to what extent pre-existing weathered material might be represented. To this end, in addition to eight WS-2 core samples, eight reference samples were analysed to determine their entire elemental content. The latter samples comprised: (i) two diverse diamicts from west Gower (a LGM glacitectonite with documented ISB material and a pre-LGM fine colluvial sediment considered to represent reworked soil with aeolian inputs); (ii) glacigenic, paraglacial and periglacial sediments from Rotherslade in south-east Gower, which are virtually only of Welsh Coalfield or local (limestone) slope origins; and (iii) classic 'Irish Sea tills' (see Table 1 for details of sites and references). Sample geochemistry was determined using a Rigaku NEX-CG EDXRF (www.rigaku.com/products/xrf/nexcg) following gentle air-drying of 5 g samples, which were ground, packed into 32-mm diameter cups and sealed with 4-µm thick Prolene film.

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

Results

Sediment core analysis

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

Facies 1A is a yellowish-brown, homogeneous, loosely consolidated, massive, matrix-supported diamict (Dmm; codes after Eyles *et al*. 1983; Evans & Benn 2004). The matrix consists of silt to fine sand, with minor amounts of clay. Clast content is typically ~10-15%. Clasts are granules or fine to medium, subangular to subrounded, predominantly sandstone (Old Red Sandstone and Coal Measures and quartzitic) pebbles. There is apparently no preferred orientation of clast a-axes, except for possible subhorizontal alignment in one 15-cm-thick, relatively clast-rich zone. Facies 1B consists of brownish-yellow to brown, interstratified silty to sandy diamicts Dmm/Dml and Dcm/Gm (1B1), silty diamicts Dmm/Dml and slightly gravelly massive silts Fm (1B2). Individual beds range in thickness from 10 cm to >1.5 m. Facies 1B appears more compact than 1A. Clast content ranges from 7.5 to 40% (1B1) and from 2.5 to 15% (1B2). Clast size in 1B2 is similar to that in facies 1A, but 1B1 units are coarser and also contain large pebbles. Irrespective of size, clasts are mostly subangular, with similar lithologies to facies 1A. Whilst mostly massive in character, both 1B1 and 1B2 show localised stratification with cm-scale (dis)continuous laminae, pods or lenses of sediment that is either coarser or finer than the surrounding matrix. Lamination is often highlighted by Fe/Mn staining. In places, facies 1B1 shows a preferred clast a-axis orientation, commonly aligned with nearby (inclined) bed contacts. A few fractured clasts in 1B1/2 are seemingly strung out (at angles compatible with bed contacts and clast fabrics), and some circular structures of finer clasts are aligned with and wrapped around coarser clasts.

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

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

Electrical resistivity

The 3D field grid survey (Fig. 7) shows two distinctive resistivity units: an upper unit with relatively high (>~175 Ωm) and an underlying one with low (<100 Ωm) resistivity. Low resistivity and high normalised chargeability values were found in the lower parts of the core. These parts are significantly more clayey than the upper parts, and *in-situ* measurements on the core sediments (Fig. 6; Spalding 2010) confirm low resistivity below ~7 m depth. We are confident therefore that the 'low-resistivity' unit in the field survey corresponds to LFA2, and logically also LFA3 (below 8.90 m), but there are some limitations with data reliability at such depths. The relatively high resistivity unit in the upper 7 m of core can be attributed to the silty and sandy diamicts of LFA1, with the high variability explained by the observed clast density and matrix texture variations in sub-units 1B1 and 1B2, which causes electrical anisotropy. The apparent gradual down-core increase in resistivity in LFA1 (Fig. 6) does not seem to correspond to any observed sedimentological characteristics.

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

XRF analysis

As regards micro-XRF elemental mapping of intact facies 2B and 3A2 samples and a sample of Broughton Bay glacitectonite from north-west Gower (Table 1; Fig. 1), the main results are summarised with images shown only for Ca (Fig. 8). All three samples were dominated by Si, K, Rb and Ba, with traces of Ti and Zr, though in different concentrations and spatial distributions. Sr content was found to be relatively high in facies 2B, virtually absent from facies 3A2 and moderate for the glacitectonite, results that differ from those obtained from XRF analysis of the ground-down samples, which showed increasing Sr content in the order 2B, 3A2 and glacitectonite. The reasons for this difference are not clear, but possibly the content is of a patchy nature. Samples 2B and 3A2 revealed low 'background' Fe abundance and Fe concentrations covering ~5% of the mapped areas. The clearest differences related to Ca content (Fig. 8). The glacitectonite has sharply-bounded concentrations of Ca (~10% of the area) up to several mm in diameter. They clearly represent previously reported marine shell fragments and foraminiferal tests (see Campbell & Shakesby 1994, 2015; Shakesby *et al.* 2000). In sample 2B, Ca forms fine specks (~1% of area) with diffuse outlines. In sample 3A2 there are slightly more abundant, slightly larger (up to 1.5 mm) specks with sharp boundaries. These are likely to be microfossil remnants since under incident-light microscopy, amongst unidentifiable calcareous fragments, Syringopora and a crinoid stem of Carboniferous age were discernible.

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

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

Discussion

Depositional origin of the moraine

Although the three LFAs are clearly glacigenic, containing mostly far-travelled Welsh Coalfield debris, their architectures suggest that none represents *in-situ* till. In addition, apart from isolated flow-shear features, there are no systematic deformation structures indicative of subglacial shearing upon deposition (cf. Evans *et al.* 2006). Instead, we envisage the W-E moraine section building up by laminar sediment gravity flows emerging from points along a static ice front, the same proglacial process thought to have carried sediment to dry valley fans in south-east Gower at Rotherslade (Hiemstra *et al.* 2009) and Hunts Bay (Shakesby & Hiemstra 2015c). Such flows would have formed a relatively even moraine crestline and smooth distal slope where closely spaced, but an undulating crestline and irregular slope where wider apart (e.g. Krzyszkowski & Zieliński 2002). This origin is indicated by the following. First, the bedding in cores WS-1 and WS-2 (at near-crest and mid-slope positions, respectively) dips consistently at angles thought to match the palaeo-surface slope (presumed to be up to ~20° locally). Second, according to the ER grid (Fig. 7), LFA1 forms lobes that thin downslope, as expected for debris flows starting at the crest. Although resistivity data reliability diminishes at depth, the LFA2 upper boundary appears relatively smooth, and therefore surface unevenness is accounted for mostly by the varying thickness of LFA1. Third, LFA1 comprises loosely consolidated, interstratified silty to sandy diamicts, silty gravels and gravelly silts. Matrices of the (sub-)units are texturally similar, with clast density variations defining crude sorting, mostly inversely graded, in facies 1B (see Fig. 7). This is common in muddy debris flow deposits (e.g. Naylor 1980), as are localised sediment deformation zones suggested by (i) variable preferred clast fabrics probably formed by basal shear in individual flows (see Menzies & Zaniewski 2003; Phillips 2006) together with isolated zones of preferred unidirectional clast fabrics, (ii) discontinuous and lenticular laminations (or boudins), (iii) circular structures (turbates), and (iv) strung-out fractured clasts, similar to those produced when medium-sized clasts are broken up in experimental debris flows (Caballero *et al.* 2014). Fourth, the increasing concentration of large, angular, exclusively limestone clasts at the base (2.5-3 m) of core WS-3 prevented deeper drilling and indicated bedrock proximity. Here, in a footslope position, the ground surface slopes at a low angle matched by the subhorizontal dip in several sedimentary sub-units which, together with the shallow sediment depth, tally with sediment gravity flows thinning downslope. The distinctive form and texture of LFA1 compared with LFA2 and LFA3 have so far been stressed, but all three have structural similarities suggesting a process link. Thus the dipping, well defined, stratified bands formed of clast density variations in LFA1 and LFA2 and isolated zones of boudinage-type laminations in LFA2 are thought to reflect coalesced sediment gravity flows, and the micro-scale bands of coarse grain and granule concentrations in massive clayey units in LFA3 are the likely basal shear zones of these flows (cf. Hiemstra *et al.* 2004).

We suggest that the Paviland Moraine was formed at the limit of a thin ice lobe that moved S and SSW to occupy the shallow basin of west Gower. Thinness of the ice is supported by scarce or absent glacigenic sediment on hillslopes much above the highest points on the moraine (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 the northern end of Rhossili Down (Campbell & Shakesby 2015). Confinement of the southern limit of the ice lobe to the peninsula is supported by: (i) glacigenic sediment in dry valley fans between Eastern Slade and Oxwich Point being relatively small in calibre, sparse and mostly mixed with limestone head, contrasting with fans immediately adjacent to the moraine where it occurs as thick discrete lenses that include some coarse clasts and a mixed glacigenic-limestone diamict; and (ii) recent bathymetric data showing no evidence of moraine development offshore from west Gower (Gibbard *et al.* 2017). We attribute the subdued morphology of the W-E section of the moraine in large part to the influence of an extensive network of sinks and passages in the underlying limestone (J. Cooper, pers. comm., 2016; cf. Krzyszkowski & Zieliński 2002) largely restricting meltwater availability at the ice front to that generating sediment gravity flows down the distal slope of the moraine. We consider that this enhanced subglacial drainage would also have influenced the position of the moraine together with the thinness of the ice limiting further extension of the ice front position. The uneven thickness of LFA1 (Fig. 7) is thought to represent separate individual sediment gravity flows, in contrast to the even thickness of the underlying lithofacies thought to represent merged flows. We consider that the well dissected nature of the Oxwich Bay section of the moraine can be attributed to its location on relatively impermeable Marros Group bedrock, which restricted substrate drainage and resulted in erosion of this section of the moraine by surface meltwater.

Certain differences in the moraine sedimentary units indicate possible differences in their origins and/or provenances. First, cluster analysis (Fig. 9) suggests that geochemically LF3A2 most closely resembles the Broughton Bay glacitectonite and two 'Irish Sea tills' (Aberdaron and Criccieth grey 'till'), whereas LFAs 1, 2 and 3B are most like the glacigenic sediments from Rotherslade, east Gower (Table 1). Second, sand-size coal or 'black wood' fragments (Riding 2007) are more abundant in LFA2B than in the underlying LF3A2. Third, calcareous microfossil fragments are more common in the fine sand fraction of LF3A2 than in LF3B. Fourth, according to Riding (2007), palynomorphs from LF2B contain mostly poorly-preserved Late Carboniferous spores whereas LF3A2 has a more diverse assemblage that includes spores of Jurassic and probable Middle Eocene age and a single Cretaceous spore. The lack of diagnostic Quaternary palynomorphs in the Paviland Moraine sediments might be considered puzzling. Certainly, Hunt (1984) found such microfossils in six British glacigenic sediments and Riding (2004) found them in each of 17 glacigenic sediment samples from elsewhere in Wales. On the other hand, Riding *et al.* (2005) noted their rarity or absence in some glacial sediment samples elsewhere in Britain, so that their absence need not necessarily conflict with a glacial origin. Fifth, LF2B and LF3A2 differ in colour.

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

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

Age of the Paviland Moraine

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

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

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

Extent of the LGM ice sheet on Gower

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

An alternative suggestion of how glacigenic sediments may have reached coastal exposures was outlined by McCarroll & McCarroll (2015). They pointed out that applying an ice-contact sediment flow origin to all south Gower sediment exposures requires an unrealistically precise configuration of the ice-sheet margin to enable delivery of glacigenic debris to all coastal sediment fans, some of which have very short dry valley or cliff-notch heads. They argue instead for paraglacial remobilisation of glacigenic sediments following variable deposition of a 'sprinkling' of erratics by LGM ice that inundated the whole peninsula and effected little erosion. Like the periglacial remobilisation origin, generation of sufficient energy within very small, low-angled catchments to transport sizeable quantities of glacigenic diamict containing large-calibre debris, much of which is undiluted, to dry valley heads is also problematic with this origin. Moreover, there are reasons to reject it for both the west and the extreme south-east of Gower. As regards west Gower: (i) assuming an LGM age for the Paviland Moraine, there was clearly substantial rather than limited glacial deposition over a wide area; and (ii) glacigenic debris is plentiful in sediment fans adjacent to the moraine (e.g. Eastern Slade; Campbell & Bowen 1989), but at most sparse and mixed with limestone debris at any distance from it, even for dry valleys that penetrate relatively far into the plateau (e.g. south of Oxwich Green; see Figs 1B and 2). In south-east Gower, at Rotherslade, there is strong evidence for a mainly glacifluvial and paraglacial sediment gravity flow origin to explain much of its considerable accumulation of glacigenic sediment, leading Hiemstra *et al.* (2009) to conclude that it was produced by an LGM ice lobe that did not extend westwards from Swansea Bay onto the south-east part of the peninsula.

If our explanation for glacigenic sediments in dry valley successions in west Gower and a previous similar explanation for them at Rotherslade in south-east Gower (Hiemstra *et al.* 2009) are correct, the 'problem' dry valley - sediment fan associations lie between these two areas on the south coast. A third ice lobe may have moved S-SSE in this section for which there is some support in: (i) the alignment of the Welsh Moor recessional moraine (Fig. 2) suggesting such an ice flow direction and not the conventionally accepted south-westerly direction (cf. Patton *et al.* 2013); (ii) glacigenic sediment commonly found virtually at all heights unlike its largely limited vertical extent in west Gower; and (iii) the rarity of ISB erratics east of Oxwich Bay compared with their 'relative abundance' in west Gower (George 1933), implying different provenances. There is no obvious morainic development near the coast, however, despite a limestone substrate. The search for a plausible origin for the delivery of similar, undiluted, unsorted glacigenic diamicts to coastal sedimentary fans needs to continue. At present, however, our 'proglacial' sediment gravity flow origin seems to offer the best working hypothesis.

Future research

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

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

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

Fourth, reliable calibrated- or numerical-age dates for glacial diamicts and associated sediments are lacking on Gower. The altitude of Arthur's Stone burial chamber (147 m a.s.l.) is substantially more than most glacial debris in west Gower, which raises doubt about the validity of the LGM ^{36}Cl date obtained from its capstone (Phillips *et al.* 1994; Bowen 1999), With few new opportunities of this sort for numerical-age dating of glacial sediments, systematic application of recent promising advances in AAR analysis (intra-crystalline protein composition; Penkman *et al.* 2008; Demarchi *et al.* 2013a, b; Tomiak *et al.* 2013) to critical Gower fossil beach remnants would re-establish a reliable AAR-based chronological framework to constrain the maximum ages of overlying glacigenic-bearing sedimentary sequences.

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

Conclusions

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

- Examination of up to ~11 m of moraine sediment cores and resistivity shows dipping beds of sands, clays and silty, sandy and clayey diamicts dominated by subangular and subrounded clasts originating from the Welsh Coalfield to the north. The dips are thought to reflect an origin by sediment gravity flows down the moraine distal slope. Less pronounced banding and laminations in the more clay-rich lower parts are attributed to laminar slope flows. Some of these flows reached adjacent dry valley heads and cliff notches along the seaward margins of the limestone plateau on which the moraine lies, where they interdigitated or mixed with contemporaneous, locally-derived limestone head. The Oxwich Bay moraine section, resting on relatively impermeable bedrock, is contrastingly heavily dissected by surface meltwater.

- We reject a Middle Pleistocene age for the moraine, previously inferred from: (i) the subdued morphology of its W-E aligned section, which we attribute instead to its mode of deposition; (ii) its supposed highly weathered nature, which is not supported by observations and geochemistry of the core sediments; and (iii) its lack of superposition on fossil beach sediments of now disputed age(s), which we attribute to moraine deposition being restricted to the limestone plateau inland of and beyond the height range of these sediments. The current stratotype status of the Llanddewi Formation should thus be abandoned and a far more likely Devensian (OIS 2) date accepted.
- A Devensian age for the Paviland Moraine requires revision of currently accepted views of the maximum extent and nature of LGM ice on Gower. Its relatively large size and the scarcity of glacigenic debris much beyond its vertical and spatial extent suggest that the moraine marks the limit of relatively thin ice in west Gower. Previous research indicated that an ice lobe occupied Swansea Bay but did not encroach onto south-east Gower. The alignment of a probable recessional moraine in north-central Gower indicates a S-SSE-flowing ice lobe may have affected central Gower.
- We suggest that moraine location and form were influenced not only by ice sheet behaviour and topography but also by substrate hydrological conditions, which may be more influential than is currently acknowledged.

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Figure captions

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

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

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

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

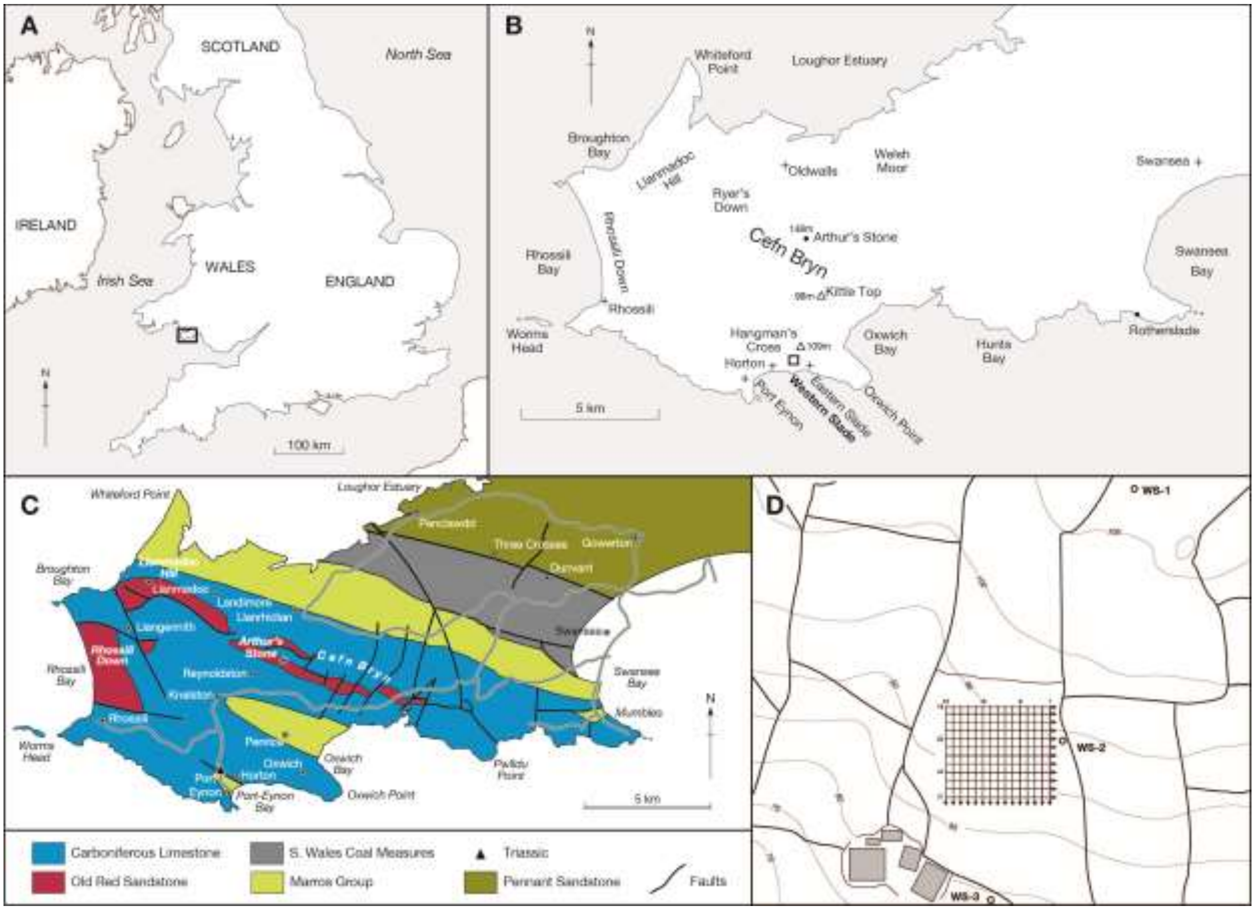
Fig. 5 The dashed line indicates the estimated extent of the Paviland Moraine in west Gower based on field observation and the Digital Elevation Map shown in Fig. 2.

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

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

Fig. 8 Micro-XRF elemental maps of Ca content for intact samples of subunits from LF2B (A), LF3A2 (B) in core WS-2 and Broughton Bay glacitectonite (C) from north-west Gower. A 100 µm X-ray source beam setting was used to obtain the 16 x 16 mm images.

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



A
SCOTLAND
North Sea
IRELAND
Irish Sea
WALES
ENGLAND
100 km
B
Whiteford Point
Loughor Estuary
Broughton Bay
Llanmadoc Hill
Oldwalls
Welsh Moor
Swansea
Ryer's Down
Arthur's Stone
Cefn Bryn
Rhossili Bay
Rhossili Down
Swansea Bay
Kittle Top
Rhossili
Worms Head
Hangman's Cross
Horton
Oxwich Bay
Hunts Bay
Rotherslade
Port Eynon
Western Slade
Eastern Slade
Oxwich Point
5 km
C
Whiteford Point
Loughor Estuary
Penclawdd
Three Crosses
Gowerton
Dunvant
Broughton Bay
Llanmadoc Hill
Llanmadoc
Landimore
Llanrhidian
Llangennith
Rhossili Down
Arthur's Stone
Cefn Bryn
Swansea
Rhossili Bay
Reynoldston
Knelston
Swansea Bay
Rhossili
Mumbles
Worms Head
Penrice
Oxwich Bay
Oxwich
Horton
Port Eynon
Port-Eynon Bay
Oxwich Point
Pwlldu Point
5 km
Carboniferous Limestone
Old Red Sandstone
S. Wales Coal Measures
Marros Group
Triassic
Pennant Sandstone
Faults
D
WS-1
WS-2
WS-3

Fig. 1

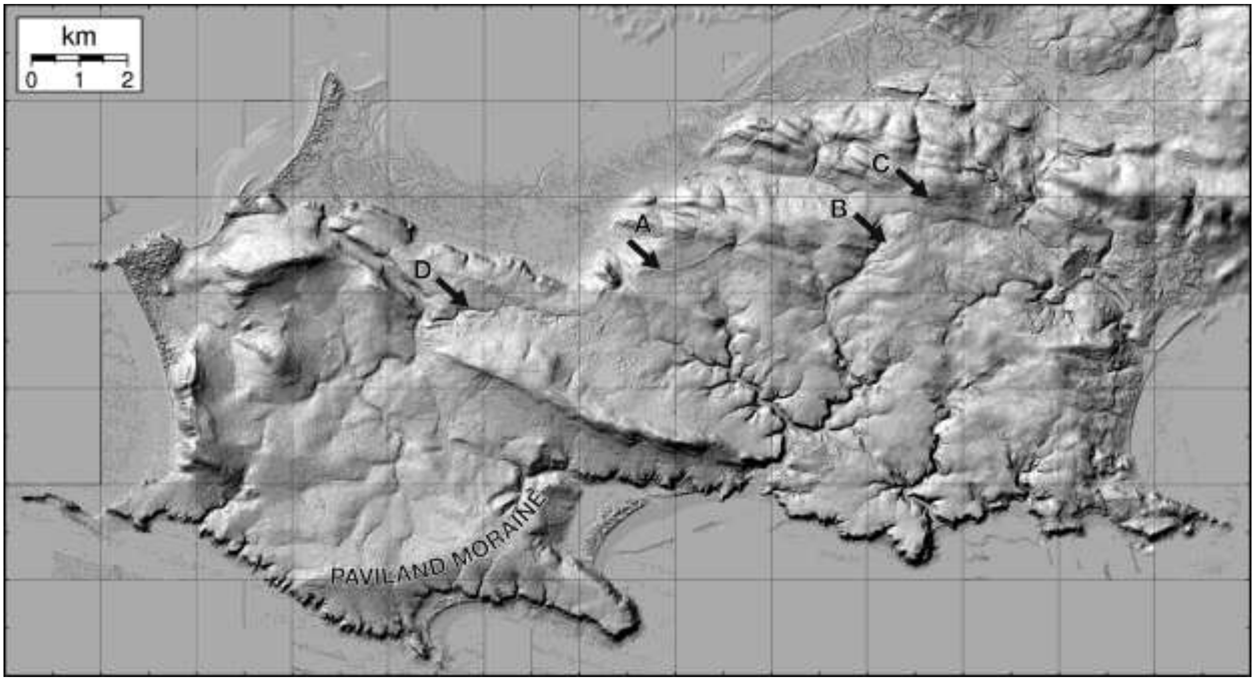


Fig. 2

Fig. 3

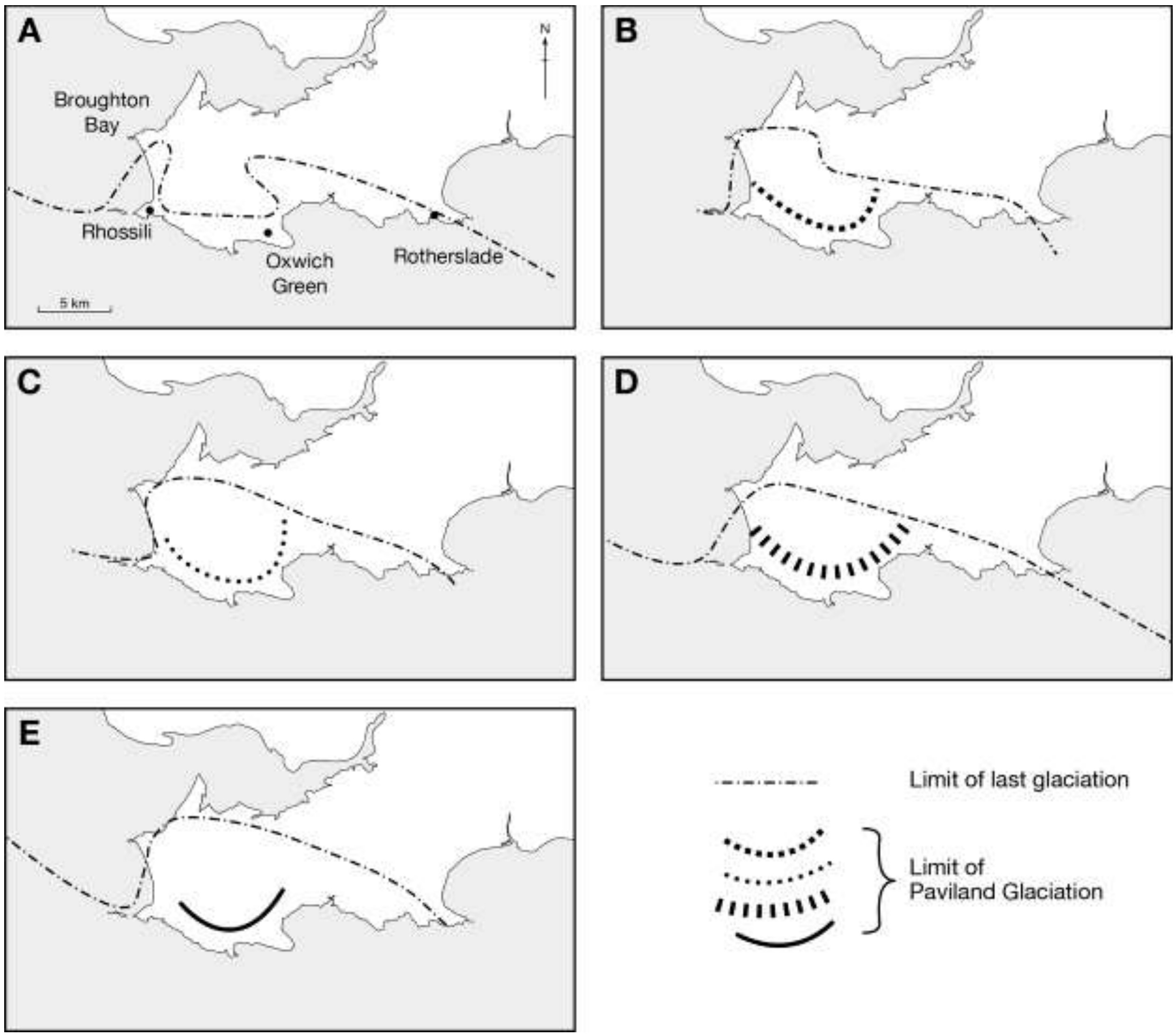

A
N
Broughton Bay
Rhossili
Oxwich Green
Rotherslade
5 km
B
C
D
E
Limit of last glaciation
Limit of Paviland Glaciation

Fig. 4

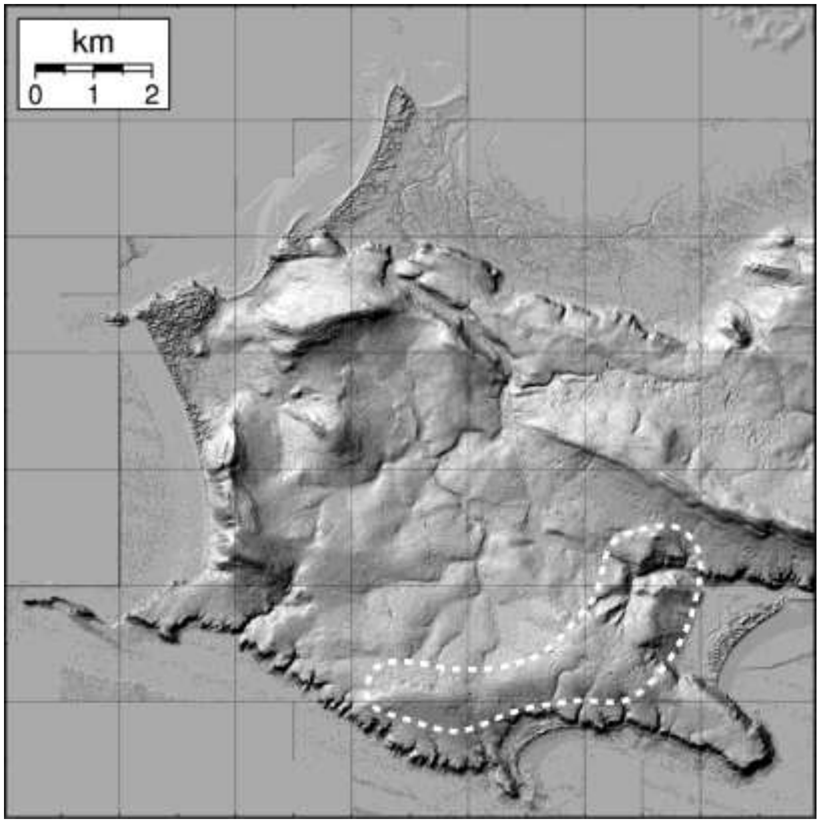


Fig. 5

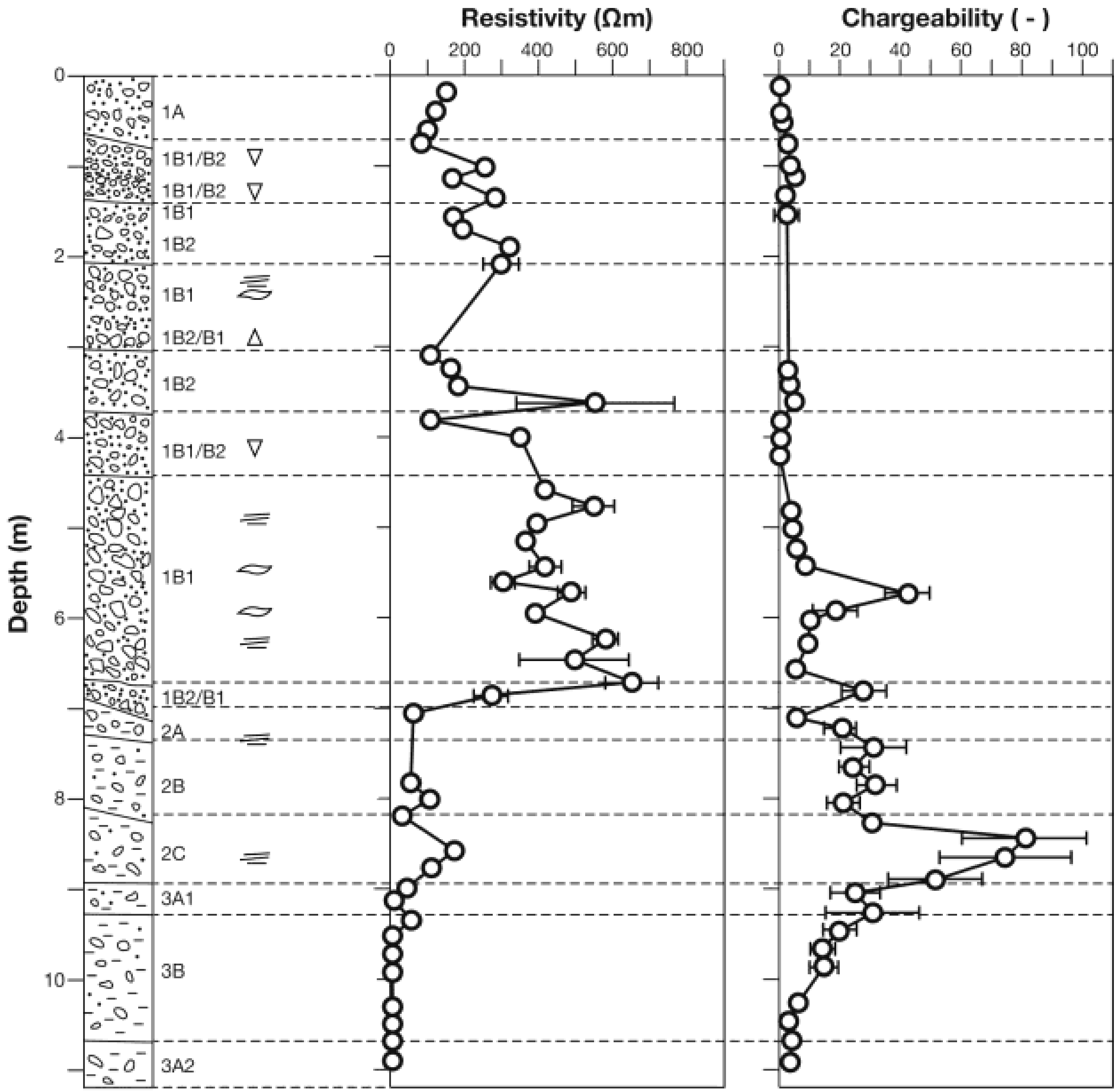

Resistivity (Ωm)
0 200 400 600 800
Chargeability (-)
0 20 40 60 80 100
Depth (m)
0 2 4 6 8 10
1A
1B1/B2
1B1/B2
1B1
1B2
1B1
1B2/B1
1B2
1B1/B2
1B1
1B2/B1
2A
2B
2C
3A1
3B
3A2

Fig. 6

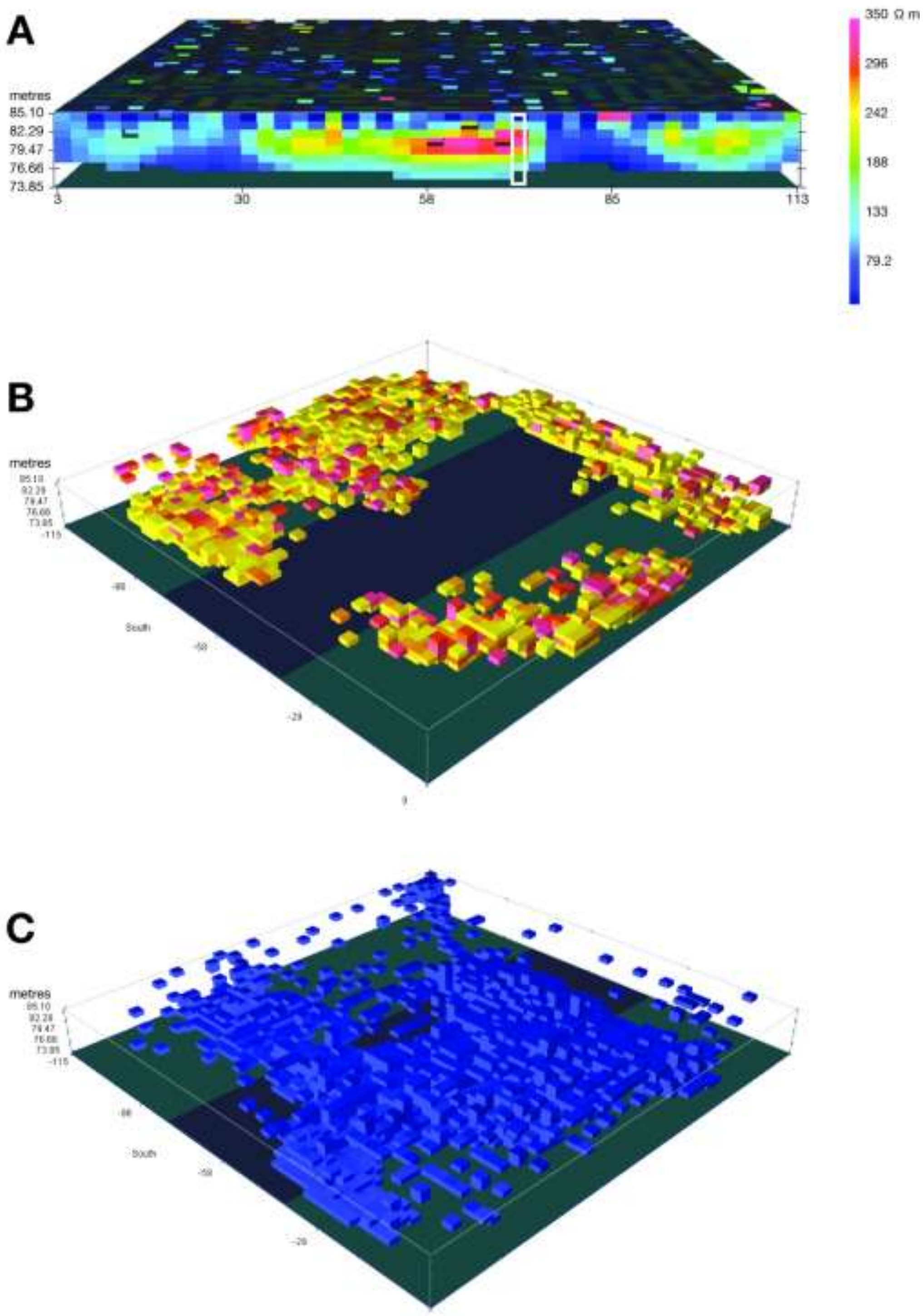

A
metres
85.10
82.29
79.47
76.66
73.85
3
30
58
85
113
350 Ω m
296
242
188
133
79.2
B
C

Fig. 7

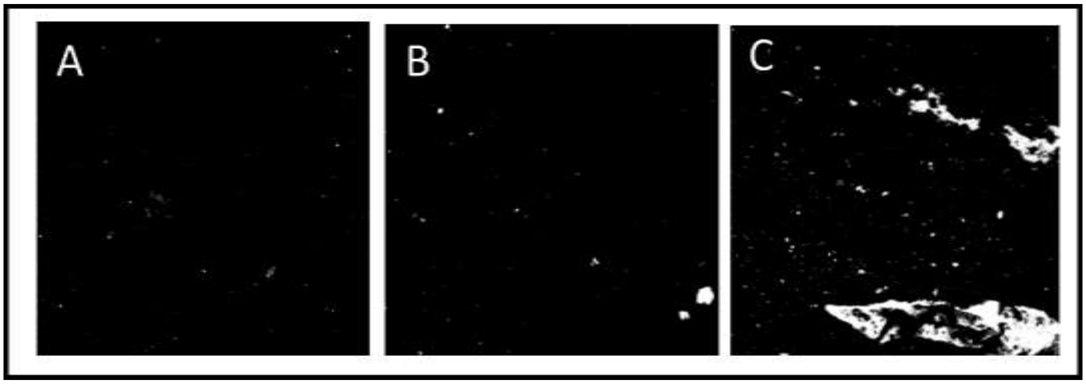


Fig. 8

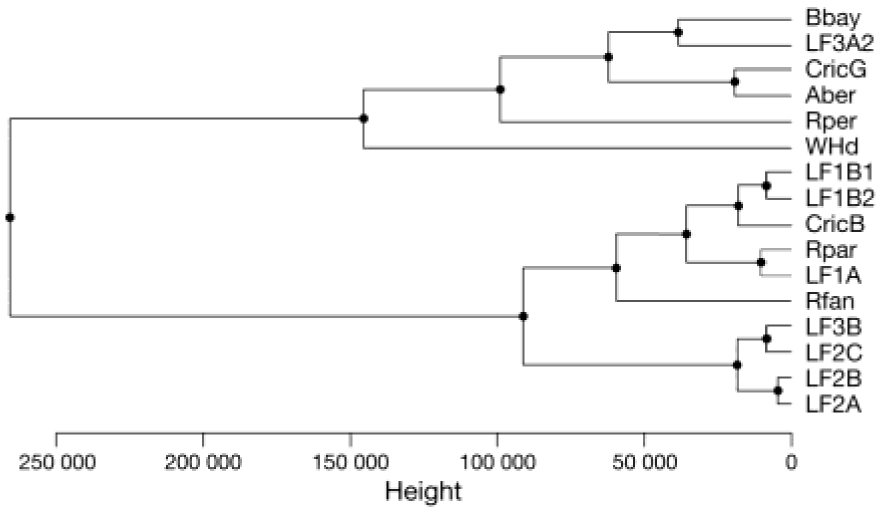

Bbay
LF3A2
CricG
Aber
Rper
WHd
LF1B1
LF1B2
CricB
Rpar
LF1A
Rfan
LF3B
LF2C
LF2B
LF2A
250 000
200 000
150 000
100 000
50 000
0
Height

Fig. 9

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

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 *et al.* (2000)
Rotherslade, E Gower	Rper	Limestone-dominant diamict (unit B1)	Locally-derived periglacial slope deposit	Hiemstra *et al.* (2009)
Rotherslade, E Gower	Rfan	Mixed lithology diamict (unit C1/C6)	Proglacial outwash	Hiemstra *et al.* (2009)
Rotherslade, E Gower	Rpar	Mixed lithology diamict (unit D)	Paraglacial mass flow	Hiemstra *et al.* (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)

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

Depth (cm)	Unit (facies)	Lithofacies association	Selected sedimentary characteris
0-74	1A	LFA1	• yellow-brown, predominantly sandy Dmm/I • clast content: 2.5 - 40% - beds/lenses of Dcı • loosely compacted • mainly subrounded sandstone clasts • alternating beds defined by variable clast de
74-113	1B1->1B2	LFA1	
113-160	1B1→1B2	LFA1	
160-167	1B1	LFA1	
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	• red-brown, clayey to silty Dmm/Dml/Dms • clast content: 2.5 - 7.5% • normally compacted • mainly subrounded sandstone clasts; locally clasts • locally discontinuous mm-cm scale stratifica boudins)
730-816	2B	LFA2	
816-890	2C	LFA2	
890-925	3A1	LFA3	• grey-brown, clayey to fine silty Dmm to (gr • clast content: 1 - 3.5% • highly compacted • mainly subrounded sandstone clasts • dispersed clasts in ill-defined, inclined band parallel a-axis fabrics
925-1065	3B	LFA3	
1065-1115	3A2	LFA3	

Table 3. Ratios for pairs of elements from core WS-2 samples. Ratios are selected for their sensitivity to weathering. Expe 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

*