New age constraints for the limit of the British-Irish Ice Sheet on the Isles of Scilly


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New age constraints for the limit of the British–Irish Ice Sheet on the Isles of Scilly

R. K. SMEDLEY,1,4 J. D. COURSE,2 D. SMALL,3 J. F. HIEMSTRA,4 G. A. T. DULLER,1 M. D. BATEMAN,3 M. J. BURKE,6 R. C. CHIVERRELL,6 C. D. CLARK,3 S. M. DAVIES,4 D. FABEL,7 D. M. GHEORGHIU,8 D. MCCARROLL,1 A. MEDIALDEA5 and S. XU7

1Department of Geography and Earth Sciences, Aberystwyth University, Ceredigion, UK
2School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, UK
3School of Geographical and Earth Sciences, University of Glasgow, UK
4Department of Geography, Swansea University, Singleton Park, Swansea, UK
5Department of Geography, University of Sheffield, UK
6School of Environmental Sciences, University of Liverpool, Liverpool, UK
7Scottish Universities Environmental Research Centre, East Kilbride, UK
8NERC Cosmogenic Isotope Analysis Facility, Scottish Enterprise Technology Park, East Kilbride, UK

ABSTRACT: The southernmost terrestrial extent of the Irish Sea Ice Stream (ISIS), which drained a large proportion of the last British–Irish Ice Sheet, impinged on to the Isles of Scilly during Marine Isotope Stage 2. However, the age of this ice limit has been contested and the interpretation that this occurred during the Last Glacial Maximum (LGM) remains controversial. This study reports new ages using optically stimulated luminescence (OSL) dating of outwash sediments at Battery, Tresco (25.3 ± 1.5 ka) and terrestrial cosmogenic nuclide exposure dating of boulders overlying till on Scilly Rock (25.9 ± 1.6 ka), which confirm that the ISIS reached the Isles of Scilly during the LGM. The ages demonstrate this ice advance on to the northern Isles of Scilly occurred at ~26 ka around the time of increased ice-rafted debris in the adjacent marine record from the continental margin, which coincided with Heinrich Event 2 at ~24 ka. OSL dating (19.6 ± 1.5 ka) of the post-glacial Hell Bay Gravel at Battery suggests there was then an ~5-ka delay between primary deposition and aeolian reworking of the glacigenic sediment, during a time when the ISIS ice front was oscillating on and around the Llyn Peninsula, ~390 km to the north.

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KEYWORDS: British–Irish Ice Sheet; ice stream; Last Glacial Maximum; OSL; TCN.

Introduction

Providing accurate age constraints for the behaviour of palaeo-ice sheets is important for testing ice-sheet models (e.g. Stokes et al., 2013). BRITICE-CHRONO is a large consortium project that is generating an extensive database constraining the retreat of the last British–Irish Ice Sheet (BIIS) from its maximum extent during Marine Isotope Stage (MIS) 2. Determining accurate ages for the proposed glacial limit on the Isles of Scilly (Scourse, 1991) is important for reconstructing ice retreat as this is the southernmost terrestrial record of a possible short-lived advance of the Irish Sea Ice Stream (ISIS) into the central Celtic Sea, previously described as a surge (Scourse et al., 1990; Scourse and Furze, 2001; Chiverrell et al., 2013). Despite some views to the contrary (Coque-Delhuille and Veyret, 1984, 1989), there has been a consensus over the position of an ice limit (Fig. 1) on the Isles of Scilly (Barrow, 1906; Mitchell and Orme, 1967; Scourse, 1991) following the first identification of erratic material in the 19th century (Smith, 1858). The age of this ice limit has, however, been contested and the interpretation that this occurred during MIS 2 remains controversial (cf. McCabe, 2008). Mitchell and Orme (1967) and Bowen (1973) argued that the glacial deposits were of Wolstonian age (MIS 6) on the basis of lithostratigraphic correlation with coastal sequences elsewhere around the Irish Sea Basin; this was later revised by Bowen (1999) to MIS 16. However, Scourse (1991) has interpreted the glacigenic sediment-landform
Scilly ice limit in a new context (Fig. 1); does it represent a lateral ice limit to the ISIS, flowing southwards from the north to the west, or does it represent a terminal limit to a larger ice body on the Irish shelf to the west with driving stresses to the west, or does it represent a terminal limit to a larger ice limit to the ISIS, flowing southwards from the north?”

As a consequence, a recent review of legacy geochronological data relating to the reconstruction of the BIS by the BRITICE-CHRONO Consortium Project (Small et al., in press) considered the existing chronology for the Isles of Scilly determined from $^{14}$C, TL, OSL and TCN dating not to be reliable for constraining ice retreat. Therefore, the aim of this paper is to report new geochronological (OSL, TCN) data for the ice advance to the Isles of Scilly. Improving the age constraints on ice advance to the Isles of Scilly is important as it will develop our understanding of changes in ice sheet dynamics relative to the IRD flux in the adjacent marine record.

Study sites and sample descriptions

A significant ice limit across the northern Isles of Scilly is delineated by boulders, glacigenic sedimentary units and associated landform elements (Fig. 2). The lithostratigraphical relationship between the sedimentary units (Fig. 2) has previously been established by Scourse (1991). An advance of the ISIS is indicated by an ice-marginal diamicton at Bread and Cheese Cove, St Martin’s, defined as the Scilly Till (Scourse, 1991) and suggested to have been subglacially emplaced and post-depositionally glacitectonized (Hiemstra et al., 2006). At this site, the ISIS advanced over pre-existing marine and contemporaneous proglacial lacustrine sediments in a similar fashion to that proposed by O’Cofaigh and Evans (2001a,b) and Evans and O’Cofaigh (2003) for Irish Sea Till deposition in south-east Ireland. The Scilly Till (Scourse, 1991) also forms the core of a series of major inter-tidal bars in the northern Isles of Scilly (White Island, Bar, Pernagie Bay and possibly also Golden Ball Bow; Fig. 2) interpreted as latero-frontal moraine loops demarcating the onshore flow of lobate ice sheet margins (Scourse, 1991; Scourse and Furze, 2001; Hiemstra et al., 2006).

Battery and Gunhill, Tresco

The coastal section at Battery, Tresco (49°58’N, 6°20’W) (Fig. 2) is described in Scourse (1991). Ice-proximal outwash sands and gravels (Tregarten Gravel) at this site are similar to outwash deposits found at Bread and Cheese Cove, St Martin’s, in association with the stratotype of the Scilly Till (Scourse, 1991). OSL ages have previously been determined for sedimentary units at both sites (Scourse et al., 2004; Evans et al., 2006a; Scourse and Rhodes, 2006), but are regarded as preliminary because full details of the samples and techniques are not provided (Table S1). Results from Bread and Cheese Cove suggest that the Scilly Till developed glacitectonic structures after $49 \pm 3$ ka, producing a till largely derived from sediments deposited during MIS 5 (Evans et al., 2006a).

Four deglacial, ice-proximal, lenses consisting of well-sorted sands containing rounded to sub-rounded erratic clasts represent the Tregarten Gravel at Battery, and are interbedded with gelifluctates correlated with the Bread and Cheese Breccia (Fig. 3); this sequence is described and interpreted in Scourse (1991). The gelifluctates sampled for OSL dating represent sediment flows down the slopes of the valley transverse to the palaeocurrent direction. The erratic clasts within the sand lenses form gravel lags at the base, with the palaeocurrent direction inferred to have been from west to east. Four sedimentary samples (T4BATT01, T4BATT03, T4BATT04 and T4BATT05) were taken from the Tregarten Gravel at Battery for OSL dating (Fig. 3). Sample T4BATT01 was taken from horizontally laminated medium-to-coarse sand at a depth of 3 m. Sample T4BATT03 was taken at a depth of 1.8 m, from a 0.4 m-thick channel-fill unit composed of planar cross-set, fine-to-medium sand and granular gravel. Sample T4BATT04 was taken from the section at a depth of 2.8 m and is composed of horizontally stratified, fine-to-medium sand. Finally, sample T4BATT05 was the lowest sample taken, at a depth of 2.5 m, from horizontally stratified medium sand and some granular gravel.

A fifth OSL sample (T4BATT06) was taken at Battery from a depth of 1 m within a unit of horizontally stratified silt-to-medium sand (Fig. 3) comprising the post-glacial Hell Bay Gravel that caps the Tregarten Gravel (Fig. 2). The Hell
Figure 2. Location of the Isles of Scilly in south-west Britain (a). The northern Isles of Scilly with the sites and associated dates discussed in the text where the inferred maximum ice limit is also shown (b). The lithostratigraphic models for the southern and northern Isles of Scilly (c; Scourse, 1991; Scourse and Furze, 2001; Scourse et al., 2009a). The Scilly Till and Tregarthen Gravel represent primary in situ glacigenic units. The Hell Bay Gravel represents a soliflucted admixture of Old Man Sandloess, Tregarthen Gravel and Scilly Till. The Bread and Cheese Breccia and upper Porthloo Breccia represent a final phase of solifluxion.
Bay Gravel is interpreted as gelifluctuates derived from the glacigenic units (Scilly Till, Tregarthen Gravel) deposited penecontemporaneously with widespread sandloess (Old Man Sandloess) associated with the Scilly Till. Scourse (1991) has interpreted the Old Man Sandloess as genetically associated with the glacial event. Two TL ages both of 18.6 ± 3.7 ka (Wintle, 1981) and an OSL age of 20 ± 7 ka (Smith et al., 1990) have previously been published for the deposition of the Old Man Sandloess.

On Gunhill, and northern Tresco in general, there are a number of isolated boulders, and some erratic clasts at the surface (Fig. 3a); two boulders and one erratic clast were sampled for TCN dating. Sample T4TRE01 was taken from a granite boulder proximal to a tor displaying some signs of glacial modification (cf. McCarroll et al., 2010). Sample T4TRE02 was collected from a large tabular granite boulder that has been moved ca. 50 m from its parent tor. The upper surface of this boulder displays no weathering pits or runnels, suggesting that it has either been overturned or had overlying material removed. Given the flat nature of the top surface, it is likely that separation occurred along a pre-existing joint within the granite bedrock. The sampled boulder occurs at the same altitude as the parent tor; thus, it is unlikely that periglacial processes, such as boulder ploughing (Ballantyne, 2001), could have separated the boulder from its parent tor, overturned it and moved it to its present position. This boulder occurs at an elevation of ~32 m OD which is within the limit of storm waves on Scilly (see discussion of Scilly Rock below) but is shielded from wave activity by the higher ridge forming the northern coast of Tresco. The site is now fully vegetated, whereas storm-influenced contexts are devoid of soil and vegetation. Given this geomorphological context, it is likely that the only mechanism that could have been responsible for boulder mobilization is ice. Sample T4TRE03 was obtained from a cobble clast sampled from the surface and within the maximum extent of glacial deposits (Scourse, 1991). The cobble was a grey, coarse-grained, non-foliated rock composed of >90% quartz. No sedimentary structures

Figure 3. Battery and Gunhill sites on the Isles of Scilly (a) and the sedimentary section at Battery shown as a photograph (b) and interpretation (c), including the sedimentary logs (d). Also shown are the five samples taken for OSL dating (samples T4BATT01, T4BATT03, T4BATT04, T4BATT05 and T4BATT06).

1 An age for sample 741al was reported in Scourse (1991) however, this sample does not feature in the original publication by Smith et al. (1990) and so cannot be included here.
were visible and during crushing the rock fractured through the quartz crystals. It is thus identified as a quartzite and bears affinity to the Holyhead quartzite (Phillips, 1991) and bedrock found in eastern Ireland (Brück and Reeves, 1976).

The Isles of Scilly are composed entirely of Variscan granite of the Cornubian batholith; therefore, the last is interpreted as an erratic probably from exposures on the east coast of Ireland and on Anglesey in Wales within the trunk of the ISIS. A full description of the lithologies and likely bedrock sources of erratics from the Isles of Scilly is included as Appendix 2 in Scourse (1991).

Shipman Head, Bryher

A linear collection of free-standing boulders positioned just inside the ice limit on Shipman Head (49°57′N, 6°21′W), Bryher, has been interpreted as a ‘boulder moraine’ (McCarron et al., 2010). The limit is further marked by a change in the character of granite tors from heavily eroded forms north of the ice limit to highly ornate castellated or inverted as the underside contains a network of weathering fissures. This material is currently being actively eroded by storm waves, which have been observed to break over the summit of the island (Fig. 4b), so only fragments remain in the more protected situations under large boulders. The preliminary field interpretation of the Scilly Rock boulder accumulation was that it was glacial in origin, so a number of the boulders that were deposited on the potential glacial material (e.g. Fig. 4c) were sampled for TCN analysis (T4SCI01, T4SCI02 and T4SCI03).

Methods

OSL dating

All five samples for OSL dating were collected in opaque tubes that were hammered into the sedimentary section to prevent exposure to sunlight during sample collection. External beta dose-rates were determined for OSL dating using inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectroscopy (ICP-AES), while the external gamma dose-rates were determined using in situ gamma spectrometry (Table 1). The external beta dose-rates were also determined using a Risø GM-25-5 beta counter to assess the accuracy of these measurements; the results were within uncertainties of the beta dose-rates determined using the ICP analyses. In addition, the external gamma dose-rates were calculated using the chemical concentrations determined from ICP-MS and compared with the gamma dose-rates determined using in situ gamma spectrometry. The external gamma dose-rates for sample T4BATT06 were similar when determined using the field gamma spectrometry (1.14 ± 0.07 Gy ka⁻¹) and ICP-MS results (1.08 ± 0.08 Gy ka⁻¹). Sample T4BATT06 was taken from a thick sedimentary unit >0.3 m away from any boundaries and so the ICP-MS results provided an accurate estimate of the gamma dose-rate that was similar to the dose-rate determined using in situ gamma spectrometry. However, the external gamma dose-rates determined using field gamma spectrometry for the four samples taken from the Tregarthen Gravel were 0.9 Gy ka⁻¹ (T4BATT01), 0.3 Gy ka⁻¹ (T4BATT03), 0.7 Gy ka⁻¹ (T4BATT04) and 0.6 Gy ka⁻¹ (T4BATT05) higher than those determined using the ICP results; this is calculated relative to the central value of the gamma dose-rate and excluding uncertainties, which are typically 10−15% of the gamma dose-rate. The differences for the four samples from the Tregarthen Gravel are probably because these samples were taken from units that were thinner than the effective range of gamma rays (~0.3 m), and so field gamma spectrometry was required to accurately determine the external gamma dose-rate in situ. Given the challenging nature of the thin sand lenses sampled from the island from the rest (Fig. 4a). It was not possible to land on this south-western part of the island, so all the observations below relate to the larger north-eastern portion. The linear boulder feature is located along the central spine of the island at its highest elevation. The boulders forming this feature are all granite and vary in size from cobbles to >10 m. Many of the boulders rest on the solid granite without any matrix present, but some rest on a diamicton matrix consisting of very poorly sorted silty sand with some clay containing abundant erratic clasts. This diamicton was sampled for micromorphological analyses to determine the depositional context of this sediment. Although no large erratics were observed, the lithic assemblage of smaller clasts was identical to that found in the Hell Bay Gravel, Scilly Till and Tregarthen Gravel, which are notably rich in Cretaceous flint, and red and grey sandstones (Scourse, 1991). Also, some of the clasts are clearly faceted and striated. This material is currently being actively eroded by storm waves, which have been observed to break over the summit of the island (Fig. 4b), so only fragments remain in the more protected situations under large boulders. The preliminary field interpretation of the Scilly Rock boulder accumulation was that it was glacial in origin, so a number of the boulders that were deposited on the potential glacial material (e.g. Fig. 4c) were sampled for TCN analysis (T4SCI01, T4SCI02 and T4SCI03).
with a 90Sr/90Y beta source (Bøtter-Jensen et al., 2005) was incorporated into the calculation of the equivalent dose ($D_e$) values. The preheat temperature was determined from a dose-recovery preheat experiment. The signal was recorded at 125 °C for a total of 1 s, where the OSL signal was summed over the first 0.1 s of stimulation and the background measured by accelerator mass spectrometry (AMS) at SUERC, using procedures based on Child et al. (2000). The $^{10}$Be/$^9$Be ratios were measured by accelerator mass spectrometry (AMS) at SUERC (Xu et al., 2010) and $^{10}$Be exposure ages were calculated using the CRONUS-Earth online calculator (Table 2; Balco et al., 2008). See Table S2 for details on the chemistry and AMS data for these analyses. Exposure ages presented are based on the time-dependent $L_m$ scaling (Lal, 1991; Stone, 2000) and assuming an erosion rate of 1 mm ka$^{-1}$. Assuming an erosion rate of 0 mm ka$^{-1}$ would change our ages by <3% and not impact upon any conclusions of this study (Table 2).

**TCN dating**

Eight samples from three locations inferred to be within the maximum extent of the ISIS were collected for analysis of in situ produced $^{10}$Be in quartz (Table 2). Shielding from surrounding topography was measured and corrected for using the CRONUS-Earth online calculator (Table 2; Balco et al., 2008). The boulder samples were chiselled from upper boulder surfaces and the cobble sample (T4TRE03) was collected as a whole clast.

Samples were crushed and washed at the University of Glasgow. Quartz was separated from the 250–500 μm fraction using standard mineral separation techniques and purified by ultrasonication in 2% HF/HNO₃ to remove remaining contaminants and meteoric $^{10}$Be. Quartz purity was assessed by measuring the aluminium content using flame atomic absorption spectrometry. Beryllium extraction was carried out at the Cosmogenic Isotope Analysis Facility – Scottish Universities Environmental Research Centre (CI AF – SUERC), using procedures based on Child et al. (2000). The $^{10}$Be/$^9$Be ratios were measured by accelerator mass spectrometry (AMS) at SUERC (Xu et al., 2010) and $^{10}$Be exposure ages were calculated using the CRONUS-Earth online calculator (Table 2; Balco et al., 2008). See Table S2 for details on the chemistry and AMS data for these analyses. Exposure ages presented are based on the time-dependent $L_m$ scaling (Lal, 1991; Stone, 2000) and assuming an erosion rate of 1 mm ka$^{-1}$. Assuming an erosion rate of 0 mm ka$^{-1}$ would change our ages by <3% and not impact upon any conclusions of this study (Table 2).
Concentrations of K, Rb, U and Th determined for OSL dating using ICP-MS and ICP-AES analysis, presented to the appropriate decimal places according to the associated detection limits. The beta dose-rates were calculated using the conversion factors of Guerin (2011) and beta dose-rate attenuation factors of Guerin et al. (2012). Gamma dose-rates were measured using a portable gamma spectrometer. Water contents of 17% were applied and are expressed as a percentage of the mass of dry sediment. The water contents were estimated from the field and saturated water contents, and environmental history for each sample. Cosmic dose-rates were determined in accordance with Prescott and Hutton (1994). Dose-rates were calculated using the Dose Rate and Age Calculator (DRAC; Durcan et al., 2015). Note that the full sample codes include a prefix of Aber209/.

Table 1. Sample Depth (m) K (%) Rb (ppm) U (ppm) Th (ppm) Beta dose-rate Gamma dose-rate Total dose-rate

T4BATT01 3.0 ± 2.1 4.3 ± 4.3 1.5 ± 0.1
T4BATT03 2.8 ± 0.1 5.4 ± 0.5 1.6 ± 0.1
T4BATT04 2.8 ± 0.1 5.4 ± 0.5 1.6 ± 0.1
T4BATT05 2.3 ± 0.1 4.3 ± 0.5 1.5 ± 0.1
T4BATT06 1.0 ± 0.1 2.0 ± 0.2 1.0 ± 0.1


Micromorphological techniques (Balco et al., 2012; Young et al., 2013). Two independently calibrated local production rates are available from the British Isles: (i) the Loch Lomond production rate (LLPR) (Fabel et al., 2012) and (ii) the Glen Roy production rate (GRPR) (Small and Fabel, 2015). These production rates agree within uncertainties (3.9 ± 0.18 and 4.26 ± 0.21 atoms g⁻¹ a⁻¹, respectively). The LLPR is preferred in this study as it is derived from direct age control provided by limiting radiocarbon ages (MacLeod et al., 2011), instead of the assumed ages of tephra within a varve chronology (MacLeod et al., 2015) used to determine the GRPR.

Results

Shipman Head, Bryher

The boulder samples from Shipman Head on Bryher were collected to assess the reliability of the exposure age obtained by McCarroll et al. (2010). Re-sampling of the top surface of the boulder (T4SH101) produced an exposure age of 23.8 ± 1.6 ka (Table 2), which agrees with the published TCN age (22.2 ± 1.3 ka). The sample collected from the underside of the boulder (T4SH102) produced an apparent exposure age of 231.8 ± 14.8 ka. Such a prolonged period of exposure before overturning means that the ¹⁰Be inventory measured from the upper surface will include a significant muonic contribution as muons can produce ¹⁰Be at depths >3 m (Braucher et al., 2003). A simple model of ¹⁰Be concentration with depth assuming a total period of exposure before overturning equivalent to the apparent exposure age of 231 ka and no prior inheritance has been determined following Granger and Smith (2000) (Fig. 5). While this model is a first-order quantification of the inherited ¹⁰Be inventory due to muons, it demonstrates that a significant proportion (~20%) of the measured ¹⁰Be inventory from the top surface is due to production by muons during exposure before overturning. This level of inheritance would produce an apparent exposure age which overestimates the true age of exposure by ~5 ka, suggesting that overturning occurred between ca. 19 and 17 ka based on the ages from the upper surface of the boulder in this study and McCarroll et al. (2010). While understanding of muon interaction cross-sections has continued to improve (cf. Phillips et al., 2016), the non-trivial level of inheritance
due to such a prolonged period of prior exposure will produce a spurious apparent exposure age for the boulder’s top surface regardless of the depth-production model used.

Scilly Rock

Diamicton

Microscopically, the diamicton is characterized as matrix supported, albeit with a variable grain density. It shows an abundance of randomly orientated, elongated, irregularly shaped pores, but there are also sets of planar fractures that display regular, symmetrical geometric patterns (subhorizontal and steeply inclined planes), which was corroborated by μCT analysis (Fig. 6a). Pebbles in the diamicton are granitic, often subangular with irregular outlines, showing evidence of in situ weathering (exfoliation, rind formation and biotite alteration). Silt and sand grains in the diamicton are highly variable in terms of shape and roundness, and display strong preferred long-axis orientation (micro-fabric) in places. Locally, lineaments and associated turbate structures can be

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lat.</th>
<th>Long.</th>
<th>Alt. (m)</th>
<th>Thickness (cm)</th>
<th>Shielding$^*$</th>
<th>$^{10}$Be conc. (at g$^{-1}$)$^{†}$</th>
<th>$^{10}$Be conc. ±</th>
<th>$1$ mm ka$^{-1}$ Exposure age (ka)$^{‡}$</th>
<th>$0$ mm ka$^{-1}$ Exposure age (ka)$^{‡}$</th>
</tr>
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<tr>
<td>T4SHI01</td>
<td>49.965</td>
<td>−6.360</td>
<td>15</td>
<td>1.3</td>
<td>0.9854</td>
<td>94,100</td>
<td>4366</td>
<td>23.8 ± 1.6 (1.1)</td>
<td>23.3 ± 1.4 (1.1)</td>
</tr>
<tr>
<td>T4SHI02</td>
<td>49.965</td>
<td>−6.360</td>
<td>15</td>
<td>1.1</td>
<td>0.9972</td>
<td>745,800</td>
<td>14,872</td>
<td>231.8 ± 14.8 (5.9)</td>
<td>193.0 ± 8.7 (4.0)</td>
</tr>
<tr>
<td>T4SCI01</td>
<td>49.957</td>
<td>−6.379</td>
<td>18</td>
<td>1.3</td>
<td>1</td>
<td>106,200</td>
<td>3723</td>
<td>26.7 ± 1.6 (1.0)</td>
<td>26.1 ± 1.4 (0.9)</td>
</tr>
<tr>
<td>T4SCI02</td>
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<td>−6.379</td>
<td>18</td>
<td>3</td>
<td>0.999997</td>
<td>171,900</td>
<td>4686</td>
<td>44.0 ± 2.5 (1.3)</td>
<td>53.0 ± 2.0 (1.2)</td>
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<tr>
<td>T4SCI03</td>
<td>49.957</td>
<td>−6.379</td>
<td>15</td>
<td>3.7</td>
<td>0.9986</td>
<td>97,500</td>
<td>3776</td>
<td>25.0 ± 1.5 (1.0)</td>
<td>24.5 ± 1.3 (0.9)</td>
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<tr>
<td>T4TRE01</td>
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<td>−6.345</td>
<td>30</td>
<td>2.5</td>
<td>0.999997</td>
<td>206,100</td>
<td>5527</td>
<td>52.9 ± 3.0 (1.5)</td>
<td>50.7 ± 2.4 (1.4)</td>
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<tr>
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<td>49.965</td>
<td>−6.349</td>
<td>32</td>
<td>2.4</td>
<td>1</td>
<td>121,300</td>
<td>4111</td>
<td>30.4 ± 1.8 (1.1)</td>
<td>29.6 ± 1.5 (1.0)</td>
</tr>
<tr>
<td>T4TRE03</td>
<td>49.965</td>
<td>−6.349</td>
<td>20</td>
<td>5.3</td>
<td>1</td>
<td>98,100</td>
<td>3500</td>
<td>25.3 ± 1.5 (0.9)</td>
<td>24.7 ± 1.3 (0.8)</td>
</tr>
</tbody>
</table>

$^*$Calculated using the CRONUS calculator (Balco et al., 2008), available at: hess.ess.washington.edu/math/general/skyline_input.php.

$^†$Be analyses were standardized to NIST27900 with $^{10}$Be/$^{9}$Be taken as $2.79 \times 10^{-11}$. A process blank correction of $5.89 \pm 1.04 \times 10^{-15}$ was applied to all samples. Concentrations have been rounded to the nearest 100 atoms.

$^‡$Exposure ages calculated using the CRONUS calculator developmental version; Wrapper script 2.2, Main calculator 2.1, Constants 2.2.1, Muons 1.1; hess.ess.washington.edu/math/al_be_v22/al_be_calibrate_v22.php; accessed 25 November 2015 (Balco et al., 2008), Lm scaling, assuming a density of 2.6 g cm$^{-3}$. Analytical uncertainties are given in parentheses.

observed (Fig. 6b), both of which can be taken as evidence of simple shear deformation (see Hiemstra and Rijsdijk, 2003). µCT analysis was also used to corroborate the suggested micro-fabric signal. Two samples, each consisting of several thousands of grains, show that there are subhorizontal modes in the micro-fabric (Fig. 6c), although the calculated eigenvalues are only moderately strong. It is reasonable to assume that the signals reflect some form of flow or strain and are related either to depositional or to deformational processes.

The predominantly silty matrix is heterogeneous, where there are zones enriched in clay around large pebbles (possibly related to granite weathering) and other parts that are distinctly sandier. In some places, a network of silty to sandy 'tracks' delineate diamictic aggregates, which is probably the reason for the fragmented nature of the diamicton. The tracks look flushed or have a fluidized appearance and they seem to be associated with the irregularly shaped pores and fractures described above. There is also evidence of clay illuviation in pores, which together with the tracks strongly suggest water circulation in the diamicton, most probably post-depositionally. In cross-polarized light, the diamicton shows patterns of unidirectional birefringence (plasmic fabrics; see Hiemstra, 2013), which reflects narrow zones of preferentially aligned clay particles (Fig. 6d) and are generally taken as evidence of strain within the sediment. This is probably in response to syn-depositional simple shear deformation. The orientation of the plasmic fabrics often conforms to the preferred micro-fabrics observed.

Overall, the micro-scale characteristics of the Scilly Rock diamicton strongly suggest that post-depositional processes have played a major role in the formation of the characteristics of this sediment (see also Hiemstra and Carr, 2015). Firstly, there is evidence of in situ weathering of granite clasts (including the alteration of biotite minerals to clays). Second, there is ample evidence of water movement probably occurring post-depositionally, not syn-depositionally, within
the diamicton based on the irregular nature of pore spaces, the localized effects of winnowing and fluidization, and traces of clay illuviation. There is also strong microscopic evidence of ‘primary’ strain, which is localized but consistent in terms of overall character. The geometric planar fracture patterns and the identified types of fabrics are compatible in terms of general orientations with a simple, syn-depositional shearing regime. The micro-fabric modes, the unidirectional plasmic fabrics and their close association with turbates would be consistent with a subglacial shearing environment (see van der Meer, 1993; van der Meer and Menzies, 2011; and references therein). This suggests that the diamicton analysed represents a basal till or a subglacial traction till (cf. Evans et al., 2006b) that has been post-depositionally modified.

**Age constraints**

The three TCN samples overlying the diamicton from Scilly Rock yielded apparent exposure ages of 26.7 ± 1.6, 44.8 ± 2.5 and 25.0 ± 1.5 ka (Table 2). Given the age correspondence (within their analytical uncertainties) of two of the samples, the oldest age (T4SCI02) appears to be an outlier and is attributed to nuclide inheritance. Samples T4SCI01 and T4SCI03 have exposure ages that agree within their analytical uncertainties (Table 2). While their geomorphological context does not allow their previous orientation to be inferred, their ages imply mobilization around the time of the LGM. Also, the boulders from which these samples were taken directly overlie erratic-bearing diamicton (see ‘Diamicton’ above), which shows that there is probably a direct relationship between the boulder and the glacial deposits. If this is the case, and considering the potential for inheritance (see ‘Shipman Head, Bryher’ above), then the remaining two Scilly Rock exposure ages constrain the timing of the LGM on the Isles of Scilly to an arithmetic mean age of 25.9 ± 1.6 ka with a range of 28.3–23.5 ka.

**Tresco**

Previous OSL studies of glacial sediments from the Isles of Scilly (Scourse and Rhodes, 2006) have reported issues with feldspar contamination in the density-separated quartz fractions. Single-grain OSL measurements of the quartz fraction separated in this study show that ~5% of the grains gave \( D_e \) values, but ~40% of these grains failed the OSL-IR depletion ratio test (Duller, 2003), which addressed issues of feldspar contamination. Typical decay curves and a dose–response curve measured for a single grain of quartz from sample T4BATT03 are shown in Fig. 7. The \( D_e \) values for single grains of quartz that passed the OSL-IR depletion ratio test (and the other criteria described above) from all five samples gave overdispersion values ranging from 37 to 43% (Fig. 8). The single-grain \( D_e \) values determined for the samples in this study are included in Tables S3–S7. The central age model (CAM) was used to determine OSL ages for these samples (Table 1) as the symmetrical distribution of \( D_e \) values did not suggest that the grains were heterogeneously bleached before burial (Fig. 8). OSL ages of 29.1 ± 1.9, 26.8 ± 2.0, 22.5 ± 1.8 and 23.7 ± 2.0 ka were determined for samples T4BATT01, T4BATT03, T4BATT04 and T4BATT05, respectively (Table 1) and constrain the deposition of the Tregarthen Gravel at Battery. The OSL age of 19.6 ± 1.5 ka for the overlying sample (T4BATT06) then determined the timing of deposition of the Hell Bay Gravel. The three TCN samples from Gunhill on Tresco associated with the OSL samples yielded apparent exposure ages of 52.9 ± 3.0 and 30.4 ± 1.8 ka (both granite boulders) and 25.3 ± 1.5 ka (quartzite erratic).

**Discussion**

The TCN concentration measured from the underside of the Shipman Head boulder and the existing TCN exposure ages from outside the inferred ice limit (McCarroll et al., 2010) indicate that the granite tors of the Isles of Scilly have a long exposure history, increasing the likelihood of nuclide inheritance in the TCN samples. This fact is highlighted by the ages presented for samples T4SCI02 and T4TRE01, which pre-date the LGM. The long exposure history highlights the potential for significant muonic contributions to \(^{10}\)Be inventories measured in large overturned boulders, demonstrated by the exposure ages obtained from the upper surface of the Shipman Head boulder (see ‘Shipman Head,
Bryher’ in the Results). These ages include roughly 20,000
\(^{10}\)Be atoms g\(^{-1}\), equivalent to
\(^{10}\)Be/\(^{24}\)C\(_2\) 5 ka of full exposure,
acquired before overturning. An age of 19–17 ka for deposi-
tion of the boulder at Shipman Head suggests that glaciation
is an unlikely agent of boulder mobilization at this time as
the ISIS is known to have retreated
\(^{24}\)C\(_2\) 500 km north of the
Isles of Scilly to the Isle of Man by
\(^{24}\)C\(_2\) 17 ka (Chiverrell
et al., 2013). Consequently, an alternative mechanism(s) must be
responsible for overturning this boulder, such as periglacial
activity or the highly energetic storm waves known to
influence the Isles of Scilly (e.g. Fig. 4a), and the usage of
the term ‘boulder moraine’ to describe the Shipman Head
feature should be discontinued.

Although the potential for nuclide inheritance suggests that
cautions need to be applied when interpreting exposure ages,
there is supporting geomorphological and sedimentary evidence
that can be used to draw some inferences on when the
ISIS impinged on to the northern Isles of Scilly. The inference
that ice was responsible for mobilization of the boulder sampled for
T4TRE02 (see ‘Sample sites’, ‘Scilly Rock’) is not
refuted by the apparent exposure age obtained from its top
surface of 30.4 ± 1.8 ka. Although this age pre-dates the
LGM, the boulder appears to be overturned due to the
absence of weathering features on its top surface and it is
likely to contain a significant muonic contribution (see
‘Shipman Head, Bryher’ in the Results), thus overestimating
the time elapsed since boulder mobilization by an indeter-
minal amount. The age therefore represents a maximum
limit on the timing of glaciation of the Isles of Scilly.

The youngest exposure age from Tresco (T4TRE03) was
obtained from an erratic quartzite clast sampled from the
surface within the maximum extent of the Hell Bay Gravel
(Scourse, 1991). Considering that the clast was exposed at the
present-day surface, it is likely that it was covered by
overlying material to some degree in the past. This would act
to attenuate the incoming cosmic radiation, reducing the
production rate of \(^{10}\)Be within the sample and resulting in an
apparent exposure age that underestimates the true age of
deposition. Although the depth and duration of cover cannot
be quantified, the extremely low relief of the sample site
precludes significant erosion of material implying that any
pre-existing cover was probably thin. As a result, the
exposure age is not corrected for any post-depositional
shielding and the resulting age is interpreted as a minimum.
The Isles of Scilly are composed entirely of Variscan granite
and so the quartzite erratic was most likely deposited by the
ISIS when it impinged upon the northern Isles of Scilly. The
exposure age of 25.3 ± 1.5 ka for sample T4TRE03 is
interpreted as a minimum limit on the timing of glaciation of
the Isles of Scilly.

The boulders from which samples T4SCI01 and T4SCI03
were collected both directly overlie glacigenic sediments (see
‘Sample sites’). While the potential for nuclide inheritance
cannot be discounted, the good agreement of these ages and
their sedimentological association suggest that their exposure
ages represent boulder mobilization by ice. Additionally,
these ages are bracketed by the maximum and minimum
limiting age control provided by the ages from Tresco, which
adds further chronological constraints to the last glaciation of
the Isles of Scilly. As a result, the TCN data suggest that the
ISIS extended to the Isles of Scilly during a time interval after
30.4 ± 1.8 ka and before 25.3 ± 1.5 ka. This agrees with the
exposure ages from Scilly Rock (T4SCI01 and T4SCI03),
which suggest ice impinged on the Isles of Scilly at 28.3–23.5
ka, with an arithmetic mean age of 25.9 ± 1.6 ka.

The new OSL ages for the deposition of the Tregarthen
Gravel associated with the Scilly Till (Scourse, 1991) at
Battery (Fig. 3) also suggest that ice was impinging on the

Isles of Scilly during MIS 2 (Table 1). Although the reliability of the preliminary ages reported by Scourse and Rhodes (2006) for the Tregarthen Gravel at Battery is difficult to assess due to the lack of information published for the analyses, the ages of 25.1 ± 2.2 and 22.7 ± 0.9 ka are consistent with the new OSL ages in this study.

The OSL ages of samples taken from the Tregarthen Gravel in this study are not in simple stratigraphic order (Fig. 3). This is unlikely to have been caused by inaccurate environmental dose-rates as these have been independently assessed using multiple methods in this study (see ‘OSL dating’). Inaccurate estimation of the water content throughout burial is also unlikely as samples were taken from within 1 m of each other in the same stratigraphic section with identical overlying and underlying sedimentary units of breccia (Fig. 3c). The OSL ages are consistent with each other within ±2σ, and this probably reflects the reproducibility of OSL dating of replicate samples from a single depositional event. An approach to determine an OSL age for the ice advance to the Isles of Scilly indicated by the Tregarthen Gravel is therefore to calculate the weighted mean and standard error of the four OSL ages (25.5 ± 1.5 ka), where the standard error was calculated using equations 21 and 22 of Aitken and Alldred (1972).

The weighted mean of the OSL ages for the Tregarthen Gravel at Battery (25.5 ± 1.5 ka) agrees with the TCN exposure ages from boulders on Scilly Rock (25.9 ± 1.6 ka), and provides strong evidence that sediments were deposited by ice during MIS 2 (Fig. 2). The OSL and TCN ages for ice advance to the northern Isles of Scilly suggest that it occurred around the time of maximum position at 23.4–24.0 cal ka BP reported for the south coast of Ireland from the youngest radiocarbon ages for reworked shell fragments within subglacial Irish Sea diamicton (Ó Cofaigh and Evans, 2007). OSL ages for proglacial outwash in southern Ireland at Whiting Bay (24.4 ± 1.8 ka; 24.2 ± 2.3 ka) and Ballycroneen (23.8 ± 2.1 ka; 21.6 ± 2.1 ka) (Ó Cofaigh et al., 2012) then suggest rapid retreat of the ISIS from its maximum position in the Celtic Sea to south-eastern Ireland at 23.7–22.9 ka (Fig. 9; Chiverrell et al., 2013), and thus retreated more rapidly than the subsequent retreat of the ISIS northwards to the Isle of Man (Chiverrell et al., 2013). While the ISIS was rapidly retreating from the Isles of Scilly to the coasts of south-east Ireland and south-west Wales, ice masses in Ireland (e.g. Ballantyne and Stone, 2015) and Wales (e.g. Hughes et al., 2016) are reported to have rapidly thinned.

The terrestrial signature for an ice advance to the northern Isles of Scilly constrained by the OSL (25.5 ± 1.5 ka) and TCN (25.9 ± 1.6 ka) ages suggests that the maximum extent of the ISIS in the Celtic Sea coincided with global LGM (Fig. 9; Clark et al., 2009). Ice impingement on to the Isles of Scilly ended around the time of Heinrich Event 2 (H2) ~24 ka as the ISIS ice front was in south-east Ireland 23.7–22.9 ka (Fig. 9; Chiverrell et al., 2013). This is shown in the IRD record from the marine core OMEX-2K at Goban Spur by an increase in IRD flux from the ISIS at ~24 ka (Fig. 9; Scourse et al., 2009a; Haapaniemi et al., 2010). The

![Figure 9](image-url)
Conclusions

The new ages reported in this study in combination with previous work provide strong evidence that ice advanced to the Isles of Scilly during MIS 2. The OSL age of 25.5 ± 1.5 ka for the deposition of ice-marginal outwash sediments at Battery, the limiting TCN exposure ages of 30.4 ± 1.8 and 25.3 ± 1.5 ka from northern Tresco, and the mean TCN exposure age of 25.9 ± 1.6 ka from boulders directly overlying till on Scilly Rock suggest that ice was impinging on the northern Isles of Scilly earlier than was previously estimated by Chiverrell et al. (2013). This implies that ice impingement on to the Isles of Scilly ended around the time of increased IRD flux in the marine record at ~24 ka associated with H2. This supports the suggestions of previous studies that ice advance and retreat on to the Isles of Scilly was related to H2 and was followed by recession of the ISIS during the warming of the GI-2 at ~23 ka. After the ISIS had receded from the Isles of Scilly, there was a delay of ~5 ka between the primary deposition and aeolian reworking of glaciogenic sediment according to the OSL age of 19.6 ± 1.5 ka for the Hell Bay Gravel. At present, there is a lack of evidence for the environmental history of the Isles of Scilly after the advance of ice and before the phase of aeolian deposition, during a time when the ISIS ice front is known to have been oscillating on and around the Llyn Peninsula, Wales. This phase of aeolian activity was then followed by a phase of active solifluction.

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Supporting Information

Table S1. Details of the ages determined from previous studies on the Isles of Scilly.

Table S2. Chemistry and AMS data for samples from the Isles of Scilly.

Table S3. $D_0$ values from OSL dating of sample T4BATT01 from the Isles of Scilly.

Table S4. $D_0$ values from OSL dating of sample T4BATT03 from the Isles of Scilly.

Table S5. $D_0$ values from OSL dating of sample T4BATT04 from the Isles of Scilly.

Table S6. $D_0$ values from OSL dating of sample T4BATT05 from the Isles of Scilly.

Table S7. $D_0$ values from OSL dating of sample T4BATT06 from the Isles of Scilly.

Abbreviations. AMS, accelerator mass spectrometry; BIS, British-Irish Ice Sheet; GI-2, Greenland Interstadial 2; GRPR, Glen Roy production rate; H2, Heinrich Event 2; ICP-AES, inductively coupled plasma atomic emission spectroscopy; ICP-MS, inductively coupled plasma mass spectrometry; IRD, ice-rafter debris; ISIS, Irish Sea Ice Stream; LLPR, Loch Lomond production rate; MIS, Marine Isotope Stage; OSL, optically stimulated luminescence; TCN, terrestrial cosmogenic nuclide; TL, thermoluminescence; µCT, micro-X-ray tomography.

References
