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Was Scotland covered by an ice sheet during Marine Isotope Stage 4? Insights from the pre-Last Glacial Maximum marine terraces of northwest Scotland

Running Title: Pre-LGM marine terraces of NW Scotland

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Abstract

Raised shorelines provide important constraints on past sea levels, glacial isostatic adjustment (GIA), and rates and directions of vertical crustal motion. Although most raised shorelines across NW Scotland relate to post-Last Glacial Maximum (LGM) glacial-isostatic rebound, many undated shorelines lie above the marine limit established from isolation basins. Here we present new optically stimulated luminescence (OSL) ages for a raised marine terrace at an elevation of 28 m in Slaggan Bay of NW Scotland. Four OSL ages suggest the feature is pre-LGM, likely Marine Isotope Stage (MIS) 3. Global mean sea levels (GMSL) during MIS 3 are thought to have been ~40-60 m below present across most of the globe. We use a pair of GIA models to determine what ice sheet and sea-level scenarios might provide an explanation for these anomalously high sea levels during MIS 3. Our results suggest that in the absence of tectonic activity, such high MIS 3 shorelines across NW Scotland require a MIS 4 ice sheet in Scotland with post-glacial rebound of the crustal depression following its demise during MIS 3 responsible for the elevated shoreline features at that time.

Keywords: British-Irish Ice Sheet, Interstadial, sea-level change, Interglacial, coastal

1. Introduction

Although global mean sea levels (GMSLs) and ice sheet volumes are reasonably well known during the Last Glacial Maximum (LGM) and the Last Interglacial, our understanding of GMSLs and ice sheet volumes during the intervening MIS 3 and MIS 4 are poorly constrained. For example, estimates of MIS 3 GMSLs range from -37 m (Pico et al., 2020) to -60 m (Siddall et al., 2008) relative to present (Gowan et al., 2021). Our understanding of ice volumes during

MIS 3 and MIS 4 are even more poorly constrained (Dalton et al., 2022a; Doughty et al., 2021). Recent work has refined our understanding of these ice sheets across North America (e.g. Dalton et al., 2019; 2022b; Pico et al., 2018), South America (e.g. Peltier et al., 2021) and Fennoscandia (Kleman et al., 2021). This recent work has led to many new global ice models to include ice during MIS 4 across much of the Northern Hemisphere including Scotland (e.g. Batchelor et al., 2019; Gowan et al., 2021). However, evidence for a MIS 4 ice sheet in Scotland and the British Isles is fragmentary but growing (Scourse, 2024). With only a handful of ages on pre-LGM bedrock ice-abraded surfaces (e.g. Rolfe et al., 2012; Gibbard et al., 2022; Hughes et al., 2022), moraines, till, or outwash fans (e.g. Duller et al., 1995; Bradwell et al., 2021; Rex et al., 2023), much of that evidence comes from ice rafted debris along the margins of the British Isles (Knutz et al., 2001; Wilson et al., 2002; Scourse et al., 2009; Peck et al., 2007; Toucanne et al., 2009; 2023; Hibbart et al., 2010; Fabien et al., 2023) but some is from anomalously elevated relative sea levels (e.g. Dawson et al., 1997; O'Cofaigh et al., 2012; Gallagher et al., 2015).

Across NW Scotland, similar to other formerly glaciated margins, higher-than-present relative sea levels (RSL) were experienced immediately following the LGM due to the delayed surface response to the unloading of former ice sheets. As glaciers are effective agents at eroding the landscape, most of these raised shorelines date to post-LGM times. The two regionally mappable raised shorelines across NW Scotland include (i) the Lateglacial shoreline, which formed immediately after the LGM, and (ii) the Post-glacial shoreline, which formed during the mid-Holocene (Smith et al., 2019). However, fragments of older shorelines have been found (e.g. Robinson, 1977; Smith et al., 2019; Dawson et al., 2023). These older shorelines are poorly dated and thus their age and importance in understanding sea-level and ice-sheet changes across Scotland remain unknown. In this study we add to a growing body of evidence on the pre-LGM ice sheets and sea-level constraints of NW Scotland (e.g. Dawson et al., 1997) by reporting the first absolute ages from one of these pre-LGM shorelines in NW Scotland north of the Isle of Skye. At Slaggan Bay, approximately 4 km SW of Greenstone Point, a marine terrace underlain by ~20 m of Quaternary deposits lies ~10 m above the Lateglacial shoreline mapped by Sissons and Dawson (1981) (Fig. 1). We obtained 4 new OSL ages from the topset and foreset deposits associated with this raised marine terrace. In addition, we note the presence of other similar features lying above the generally accepted Lateglacial shoreline across NW Scotland. We review these elevations and compare them with GIA model results to determine what ice sheet and GMSL scenarios might result in higher-than-present pre-LGM sea levels across NW Scotland. Our new results add to a growing, but still fragmentary, understanding of the pre-LGM (pre-MIS 2) ice-sheet and sea-level history of Scotland.

2. Background

2.1 Ice Sheet and Sea-level History

Ice sheets covered Scotland during the LGM when its ice sheet merged with the Fennoscandian Ice Sheet (Hughes et al., 2016) and extended to the continental shelf edge (Clark et al., 2018). Little is known about the ice sheet extent and thickness prior to the LGM (Scourse, 2024), but the region experienced multiple phases of glaciation over the last 1.1 to 2.6 Ma (Thierens et al., 2012; Gibbard et al., 2022). Currently evidence for these previous glaciations is fragmentary (Gemmell et al., 2007; Smith et al., 2019; Gibbard et al., 2022; Scourse, 2024) due in part to the erosive nature of subsequent glaciations (Merritt et al., 2019). Records of ice-rafted debris (IRD) in marine sediment cores in the North Atlantic suggested the presence of marine-terminated glaciers across western Scotland during MIS 4 (Knutz et al., 2001; Wilson et al., 2002; Hibbert et al., 2010; Peck et al., 2007; Scourse et al., 2009; Fabien et al., 2023). Marine cores also provide evidence for enhanced meltwater delivery to the surrounding oceans from the British Isles during early MIS 4 (Toucanne et al., 2023). On land, Bradwell et al. (2021) in NW Scotland and Duller et al. (1995) and Gemmell et al. (2007) in NE Scotland used OSL to date glacial-fluvial outwash deposits that suggest glacial meltwater during MIS 4 (Fig. 1a). Farther south in England and Wales, evidence for MIS 4 glaciation includes cosmogenic ages of glacial landforms (e.g. Rolfe et al., 2012; Gibbard et al., 2022; Hughes et al., 2022) and glacial-fluvial deposits (e.g. Rex et al., 2023) and tills younger than MIS5 but older than the LGM (Bowen, 1991; Merritt and Auton, 2000; Finlayson et al., 2010; Scourse, 2024). However, discussion continues as to the absolute age and origin of many of these terrestrial deposits and landforms (Clark et al., 2004; Scourse, 2024).

Following retreat of the LGM ice masses, most of Scotland underwent postglacial rebound. The highest magnitudes of uplift were located SE of our study area (e.g. Smith et al., 2006) where raised beaches and isolation basins suggest RSLs as high as 40 m during deglaciation (Shennan et al., 2018; Dawson et al., 2022). Generally, these marine limits decrease north of the Isle of Skye to an elevation of around 20 m in the vicinity of Slaggan Bay (Sissons and Dawson, 1981; Shennan et al., 2018; Simms et al., 2022) along the eastern shores of the Minch (Fig. 1). However, older, presumably higher raised marine deposits have been identified (e.g. Robinson, 1977). In other areas of Scotland (e.g. Dawson et al., 1997) and Ireland (e.g. O'Cofaigh et al., 2012; Gallagher et al., 2015) luminescence ages of these older marine deposits including raised beaches have suggested these postdate the last interglacial but pre-date the LGM. Some previous work has suggested that the elevations of these higher and presumably older marine indicators may be a result of rebound from pre-LGM ice masses (e.g. Sutherland, 1981; O' Cofaigh et al., 2012; Scourse, 2024) but to date no studies have explicitly tested these ideas with a GIA model.

2.2 Study areas

Slaggan Bay is a small cove on Greenstone Point Peninsula near the mouth of Loch Ewe, which opens into the Minch – the strait between mainland Scotland and the Outer Hebrides (Fig. 1). The whole rugged Greenstone Point headland is underlain by Neoproterozoic sandstones of the Torridon Group. Following the LGM, the headland was likely ice free by 17-16 ka (Bradwell et al., 2021). The post-LGM marine limit is thought to be around 20 m in this region (e.g. Sissons and Dawson, 1981; Shennan et al., 2018; Simms et al., 2022). Stoer Peninsula is another prominent headland about 40 km north of Slaggan Bay (Fig. 1). It too was covered by ice during the LGM and became ice free at about the same time as Slaggan Bay (Bradwell et al., 2021), or slightly earlier. However, the post-LGM marine limit is thought to be much lower here, likely less than 6 m (Hamilton et al., 2015).

3. Methods

3.1 Field Sampling

All sites were surveyed to Ordnance Datum Newlyn (OD). The marine terraces at Slaggan Bay were surveyed using a Leica 1200 differential GPS. At Stoer Peninsula, the marine terrace was levelled using a Leica Automatic Optical Level in reference to an adjacent fixed Ordnance Survey benchmark (NC00503261). In addition, the sedimentary deposits comprising the marine platforms were observed in scarps cut into both platforms. Sands for OSL dating at Slaggan Bay were sampled under a large opaque black tarpaulin sheet. Dose-rate samples were collected from each distinct layer within a distance of 40 cm above and below the sample.

3.2 Optically Stimulated Luminescence Dating

Quartz separates were prepared by treating 90-212 µm diameter grains with 27% H_2O_2, 10% HCl, and 48% HF for 40 min, and subsequent density separation with lithium polytungstate solution (densities 2.75 g/cm^3 and 2.62 g/cm^3). After quartz extraction, samples were sieved once more to narrow down the grain size fraction. For each sample the fraction with the most grains was chosen for dating. We used 3mm quartz aliquots, prepared on stainless steel discs using silicone spray. Measurements were conducted using a Risø TL/OSL-DA-20 reader, Risø National Laboratory, with a bialkali PM tube (Thorn EMI 9635QB) and Hoya U-340 filters (290-370 nm). The built-in $^{90}Sr/^{90}Y$ beta source gives a dose rate of ~100 mGy/s, and the exact dose rate was calculated for each measurement. Optical stimulation was carried out with blue LEDs (470 nm), delivering 82 mW/cm^2 to the sample. IR stimulation was from an IR LED array at 875±80 nm with 124 mW/cm^2 power at the sample. The heating rate used was 5 °C/s.

We used a Single-Aliquot Regenerative-dose (SAR) method for determination of the equivalent dose (Wintle and Murray, 2006). Dose recovery and plateau tests resulted in a preheat temperature of 180°C. Dose responses were fitted with a saturating exponential function. Samples generally showed bright signals and good recycling ratios, with negligible IR depletion. Aliquots with recycling ratios between 0.9 and 1.1, and IR depletion <10% were used for calculating the equivalent dose (Duller, 2003) based on the common age model (Galbraith, 1999). All errors are reported as 1 sigma.

U, Th, and K concentrations in the samples were measured with high resolution Ge gamma spectrometry with a Reverse Electrode Coaxial Germanium detector from Canberra Industries, Inc. No disequilibria in the uranium decay chain were observed. Water content was calculated as mass of water divided by mass of dry sample. The measured values were used with an uncertainty of 0.01. Dose rate from cosmic rays was determined from the depth of sample below the surface along with its longitude, latitude and altitude, as described by Prescott and Hutton (1994).

3.3 Glacial Isostatic Adjustment (GIA) Modeling

In order to determine what sea-level elevations for NW Scotland are reasonable over the last glacial cycle, we used the GIA model developed by Bradley et al. (2023), which is an outgrowth of several preceding models (e.g. Bradley et al., 2011) to predict past sea levels. To produce the RSL and land level predictions across our study region, we solved the generalized sea-level equation (Kendall et al., 2005, Mitrovica and Milne, 2003), including the impact of rotation and time-dependent shoreline migration combined with a 1D spherically symmetric, self-gravitating Earth model. The GIA model was run at 512 spherical harmonics giving it a resolution of ~35 km.

We considered two different ice sheet reconstructions combined with their associated earth model. The first, GLAC1D+, is a more traditional reconstruction based on the model of Tarasov et al. (2012) but modified over the British Isles and Europe by Bradley et al. (2023). It was combined with a lithosphere thickness of 71 km, an upper mantle viscosity of 5x 10^{20} Pa s, and a lower mantle viscosity of $1x10^{22}$ Pa s. Within this reconstruction, no ice is found over the British Isles including Scotland during MIS4 and GMSLs during MIS3 are no higher than -53 m below present. As there is no ice across Scotland at MIS4, the RSL and land level will be driven by the other large continental ice sheets across North America and Antarctica. The second is based on the PALEOMIST ice sheet reconstruction of Gowan et al. (2021), which contains significantly more ice in the northern Hemisphere including Scotland during MIS4 and GMSLs during MIS3 reach as high as -27 m at approximately 42 ka (Fig. 4). It was combined with an earth model with a lithosphere thickness of 71 km, an upper mantle viscosity of 5x 10^{20} Pa s, and a lower mantle viscosity of $5x10^{22}$ Pa s. Although this model is the topic of much discussion (e.g. Yokoyama et al., 2021), it nevertheless provides an ice sheet model openly available with a clear MIS4 ice sheet over the northern hemisphere ice centers including Scotland.

4. Results

4.1 Slaggan Bay

A very well-developed marine terrace with a top elevation of 28.3±1.1 m (OD) is found at Slaggan Bay (Fig 2a). The marine terrace extends for nearly 2 km between the southern shores of Slaggan Bay to a few hundred meters north of Gob a' Gheodha (Fig. 1). A similar marine terrace continues to the north but at a lower elevation of around 17.5 m OD. The higher ~28 m marine terrace is composed of a ~20 m thick succession of Quaternary deposits unconformably overlying Torridonian Sandstones (Fig. 2a,b). Although partly obscured by vegetation cover, the Quaternary section is composed of diamicton at the base, overlain by thin to medium bedded coarse, medium, and fine sands with occasional pale grey silt lenses (Fig. 2d,e,f). The tan-colored bedded sands are well sorted within each bed and overprinted with pedogenic lamellae. The top of the succession is composed of medium to very thick beds and lenses of dark brown to black gravelly coarse sand or sandy gravels with cobbles up to 20 cm in diameter (Fig. 2d). The bedding planes are wavy and the deposits have weakly developed cross-bedding, ripple cross-lamination, and imbrication. Some of the upper beds are cemented. The whole feature is draped by a 20-30 cm gravelly colluvial cover with isolated peat accumulations.

4.2 Stoer Peninsula

A well-developed paleo-wave-cut platform with a shoreline angle elevation of 25.0±0.25 m is found on Stoer Peninsula (Fig. 2c). The platform is cut into a stiff diamicton (Fig. 2g), which is found within at least the upper 1 m of a ~13 m section of Quaternary deposits overlying a near horizontal unconformity cut into the underlying Torridonian sandstone. The wave-cut platform may be composed of two distinct levels, but a non-marine origin to the upper platform cannot be ruled out.

4.3 OSL ages

We obtained 4 new OSL ages from the deposits at Slaggan Bay (Tables 1 and 2). Three ages were collected from the lower bedded sands: two from the base of the platform (GA22-12 and GA22-13) and one from the middle section of the platform (GA22-15) (Figs. 2a,b;3). The fourth age was obtained from a well-cemented bed at the top of the platform at an elevation of 25 m OD within the black gravelly sands (GA22-14; Fig. 2d). One of the samples within the lower bedded sands (GA22-12) returned a minimum age of >109 ka. The majority of aliquots from this sample were saturated and the minimum age was calculated using an equivalent dose of 2 D_0, where D_0 is the characteristic dose of the saturating exponential function. The lowest dose of the few unsaturated aliquots was ~250 Gy, representing an age of 90 ka. GA22-13 and GA22-14 both returned ages within error of 53.5±5.7 ka and 49.4±3.6 ka, respectively (Fig. 3). The fourth sample, GA22-15, from the bedded sands of the middle platform returned an age of 24.0±1.7 ka (Fig. 3).

5. Discussion

5.1 Origin, age and preservation of the Slaggan Bay high marine terrace

The Quaternary deposits comprising the 28 m terrace at Slaggan Bay are interpreted to represent a shoreline/delta. The cobbles are well rounded and oblate in shape. The cross-bedding and ripple cross-lamination indicate traction deposition and, in combination with the wavy nature of the bedding, are consistent with wave influence within a beach-like system or beach plain of an outwash delta. The overall shape of the feature is similar to other raised marine shorelines and terraces across Scotland (e.g. Sissons and Dawson, 1981). In addition, its orientation parallel to the modern coast fits that of a marine rather than fluvial origin. We thus interpret the black sandy gravels and gravelly sands at the top of the feature as topsets of the marine shoreline/delta while the bedded sands in the middle and base of the feature are the foresets of the marine shoreline/delta (Fig. 3). The diamictons both at Slaggan Bay and Stoer Peninsula are matrix-supported with an abundance of both well-rounded and angular, striated, clasts of diverse lithologies (Fig. 2f,g). Based on these characteristics, we interpret them to represent tills from a pre-LGM glaciation.

Although our 4 new OSL ages are not the same age, they clearly show that the platform is pre-LGM in age (Fig. 3). Two of the ages are within error, GA22-13 and GA22-14 at 53.5±5.7 ka and 49.4±3.6 ka, respectively. These two ages were obtained from different parts of the marine platform, GA22-13 from the foresets and GA22-14 from the topset, suggesting they best represent the age of the feature itself. One of the ages, GA22-12, is >109 ka, and may not have been fully bleached at the time of deposition or may indicate a composite landform of more than one age (e.g. Malatesta et al., 2022). The fourth age, GA22-15, is younger than the first two at 24 ka. Its younger age may suggest reworking of the deposits during the LGM. The diamicton, likely glacial in origin, is found at the base of the pre-LGM marine deposits making this till demonstrably pre-LGM in age, possibly MIS 4.

If the high marine terrace at Slaggan Bay pre-dates the LGM, how did it survive being overridden by an ice sheet? Pre-MIS 2 sedimentary deposits are known to have survived the last glaciation in a number of locations across Scotland (Merritt et al., 2019). These deposits are widespread in parts of NE Scotland where the extent and depth of glacial erosion was limited, but are relatively rare along Scotland's western seaboard. Bradwell (2013) mapped zones of past ice streaming around Loch Laxford ca. 60 km to the north of Slaggan Bay. He used the extent and degree of glacial erosional forms and the preservation of mountain-top pre-glacial debris to map zones of former fast-flowing ice and infer former areas of warm- and cold-based ice. Bradwell (2013) found that regions of intense glacial erosion were spatially interspersed with regions of very little glacial modification or preservation, which he interpreted as cold-based 'frozen-bed patches'. It is plausible that the western part of the Greenstone Peninsula was located in a slow-flowing or frozen-bed patch between zones of streaming ice on either side. The deep bathymetry of Loch Ewe and around the Summer Isles (outer Loch Broom) would have promoted ice-flow funneling and enhanced basal melting. The large glaciers flowing along these troughs would have fed into the Minch paleo-ice stream at times of maximum glaciation, leaving the higher ground and lee-side slopes of the Greenstone Point and Stoer peninsulas in regions of relatively low erosion. Numerical ice-sheet modelling by Hubbard et al. (2009) supports this idea with slow flowing (cold-based) zones existing on these headlands at various times during the last 40,000 years.

5.2 MIS 3 sea levels across Scotland

We interpret the two congruent ages (53.5 and 49.4 ka) to represent the age of the high marine terrace at Slaggan Bay. Thus, the marine terrace at Slaggan Bay provides a constraint on MIS 3 sea levels for Scotland. The elevation of the top of the platform is 28 m OD. This elevation is 8-9 m higher than the post-LGM marine limit of 19.3 m on Greenstone Point with shorelines reaching as high as 20.4 m at the northeastern edge of the peninsula in Gruinard Bay (Fig. 1; Sissons and Dawson, 1981).

Although not dated but similar to the case at Slaggan Bay, the surveyed elevations of the 25 m marine terrace at Stoer Peninsula are much higher than the ~6 m post-LGM marine limit at this location (Hamilton et al., 2015). Other undated hypothesized pre-LGM beaches are found at elevations higher than the post-LGM marine limit to the south of Slaggan Bay on the Applecross Peninsula (Robinson, 1977). Dated MIS 3 marine deposits and shorelines higher than the post-LGM marine limit have also been found on the Island of Islay (Dawson et al., 1997) farther south in Scotland and in southern Ireland (O'Cofaigh et al., 2012; Gallagher et al., 2015) suggesting fragments of these higher shorelines are not isolated to Slaggan Bay or Stoer Peninsula. What conditions would be required to produce MIS 3 RSLs higher than MIS 2 Lateglacial shorelines across NW Scotland?

5.3 Potential implications for the glacial history of NW Scotland

We compared our new MIS 3 sea-level constraints to GIA model predictions using the GLAC1D+ ice reconstruction, which contains no ice over Scotland during MIS 4, and the PALEOMIST ice sheet reconstruction, which contains significantly more ice over the northern Hemisphere including Scotland during MIS 4. The MIS 3 RSL predictions for NW Scotland differ significantly between these two models but are very similar for the LGM and post-LGM period (Fig. 4). Assuming the Slaggan Bay marine terrace formed during the period of highest MIS 3 RSLs in Scotland (at 57.5 ka according to the PALEOMIST model, 56 ka in the GLAC1D+ model, both within error of the average of the two OSL ages of 51.5±6.7 ka), the GLAC1D+ model predicts RSLs at Slaggan Bay of about -48 m, nearly 70 m lower than the observed MIS 3 RSLs. The PALEOMIST predictions for Slaggan Bay are much higher, reaching elevations as high as +12.7 m around 57 ka. Although a 15 m difference remains between our new observed MIS 3 RSLs and the predictions using the PALEOMIST reconstruction, the fit is nearly 55 m better than the GLAC1D+ reconstruction. This improvement is not simply a function of higher GMSLs within the PALEOMIST reconstruction, as at the time of the Scottish MIS 3 highstand, GMSL is lower than that of the GLAC1D+ model (Fig. 4). The better fit is due to the postglacial rebound caused by retreat of the MIS 4 ice sheet over Scotland (Fig. 4). In addition, the timing of the MIS 3 highstand in Scotland is notable within the GIA predictions. For the PALEOMIST prediction, the highest GMSLs occur at 42.5 ka, while the local Scottish MIS 3 highstand occurs at 57 ka, which agrees with our new OSL ages. Thus, the simplest way to reconcile the 28 m MIS 3 RSLs at Slaggan Bay with the lower-than-present GMSLs during MIS 3 is for an ice sheet to have existed over Scotland during MIS 4 and melted during early MIS 3. The size of the ice sheet needs refinement, as bringing the PALEOMIST predictions into agreement with our new RSL data requires a slightly larger ice mass than that of PALEOMIST. This observation contributes to the growing body of evidence for a significant ice sheet on the British Isles during MIS 4 (e.g. Siegert et al., 2001; Hibbert et al., 2010; Gallagher et al., 2015; Hughes et al., 2022; Scourse, 2024) and for GMSLs during MIS 3 to be higher than predicted from oxygen isotope records alone (e.g. Dalton et al., 2022a).

In their current form, the GIA model predictions for ice-sheet models containing ice over Scotland during MIS 4 cannot explain all discrepancies in MIS 3 RSL histories across NW Scotland and the British Isles. For example, the PALEOMIST model does not contain ice over Ireland during MIS 4, which without ice does not produce the isostatic rebound needed to generate the higher than present sea levels across southern Ireland observed at Courtmacsherry by O'Cofaigh et al. (2012)(e.g. Fig. S1). Similarly, although the observed differences in the elevations of the pre-LGM shorelines at Slaggan Bay and Stoer are on the order of 3 m, the difference between the PALEOMIST predictions of MIS 3 RSLs are closer to 13 m (e.g. Fig. S1). However, the Stoer shoreline remains undated and thus may not correlate to the same RSL highstand as Slaggan Bay. Alternatively, the ice sheet may have had a different configuration during MIS 4 than the ice sheet reconstruction of the PALEOMIST model. Another possibility for the larger difference in elevations of the post-glacial shorelines compared to the pre-LGM shorelines is that the post-glacial marine limits are underestimated near Stoer (Puckette et al., 2024).

Conclusions

We provide new OSL ages from a marine terrace 8-9 m higher than the post-LGM marine limit near Greenstone Point, NW Scotland. The ages suggest the feature dates to MIS 3 providing one of the few dated constraints on sea levels at this time for Scotland. Other similar higher-than expected marine features of unknown age are found in NW Scotland and some dated MIS 3 shorelines and marine deposits are found in other areas within the British Isles, suggesting these fragments are not isolated to Slaggan Bay. As global sea levels are thought to be 40-60 m lower than present during this time, the elevation of the marine terrace at 28 m requires a significant GIA contribution. Glacial isostatic adjustment model predictions suggest a significant ice mass over Scotland during MIS 4 could explain the anomalously high MIS 3 relative sea levels for this part of Scotland. Our work adds to a growing body of research suggesting pre-LGM features can be preserved beneath an ice sheet in the right subglacial conditions and that a significant MIS 4 ice sheet grew over Scotland.

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Tables

Table 1. Dose results for the OSL samples

Table 2. Dose rate information for the OSL samples.

Figure Legends:

Figure 1. Map of the British Isles showing the general location of our study area (a). Hillshade model of northwest Scotland (b) and satellite image of Gairloch and Greenstone Point Peninsulas (c) and Slaggan Bay (d) (from GoogleEarth) illustrating the locations of places mentioned in the text. Stars in (a) are the locations of previously reported potential MIS 3/4 sites including Courtmacsherry (1, O' Cofaigh et al., 2012), Fethard (2, Gallagher and Thorpe, 1997; O' Cofaigh et al., 2012), Isle of Islay (3, Dawson et al., 1997), Suainebost (4, Bradwell et al., 2021), Alt Odhar (5) and Howe of Byth (6)(Duller et al., 1995), Aberdeen (7, Gemmell et al., 2007), Arclid Quarry (8, Rex et al., 2023), Snowdon (9, Hughes et al., 2022), and Lundy Island (10, Rolfe et al., 2012). Blue stars in (a) represent outwash deposits while yellow stars represent beach deposits and red stars represent glacial landforms or till. Ire. = Ireland, GB = Great Britain. White triangles in (c) are the altitudes (in meters) of lateglacial shoreline features mapped by Sissons and Dawson (1981), while the dashed line represents the extent of a post-LGM ice sheet readvance known as the Wester Ross Readvance (from Robinson and Ballantyne, 1979).

Figure 2. Photographs of the marine terraces and their cover deposits at Slaggan Bay (a, b, d, e, f) and Stoer Peninsula (c, g). (a) Photograph looking south and up at the marine terrace from near the coastline below sample GA22-14 (see Figure 1). Also shown is the locations of the other OSL samples and the unconformity between the Torridonian

Sandstone below and Quaternary deposits above. (b) Photograph taken from the top of the marine terrace at Slaggan Bay looking north at the location of OSL sample GA22-14. (c) The marine terrace at Stoer. (d) The well-cemented gravelly sand and sandy gravels comprising the "topsets" of the marine platform at Slaggan Bay at the location of OSL sample GA22-14, (e), The interbedded sands and silts of the "forsets" of the marine platform at Slaggan Bay. (f) The till at the base of the Quaternary section at Slaggan Bay. (g) The till underlying and cut by the wave-cut platform at Stoer.

Figure 3. Cartoon summarizing the sedimentary deposits and geomorphology at Slaggan Bay.

Figure 4. (a) Model predictions of past GMSL (dashed lines) and RSL (solid lines) for two different GIA models, PALEOMIST (Gowan et al., 2021; red) and GLAC1D+ (Bradley et al., 2023; black). Also shown are the age and elevation of the marine platform-based RSL observations from Slaggan Bay (grey boxes) as well as the periods of ice cover within the two GIA models, PALEOMIST (Gowan et al., 2021, blue box) and GLAC1D+ (Bradley et al., 2023; hashed box).

Supporting Information

Fig. S1. PALEOMIST predictions or RSL for Stoer, Slaggan Bay, and Courtmacsherry.

Figure 1.

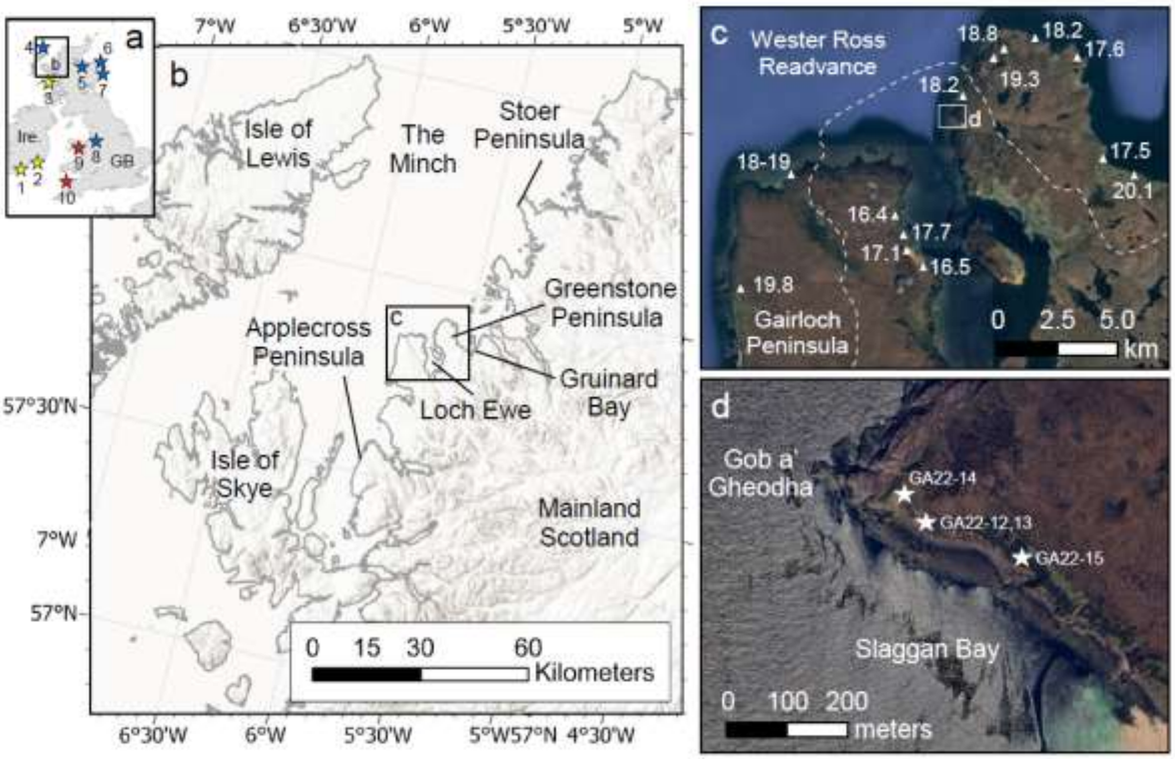
a
Ire.
GB
b
7°W
6°30'W
6°W
5°30'W
5°W
Isle of Lewis
The Minch
Stoer Peninsula
Greenstone Peninsula
Applecross Peninsula
Gruinard Bay
Loch Ewe
Isle of Skye
Mainland Scotland
57°30'N
7°W
57°N
0 15 30 60
Kilometers
6°30'W
6°W
5°30'W
5°W57°N
4°30'W
c
Wester Ross Readvance
18.8
18.2
17.6
19.3
18.2
d
18-19
17.5
20.1
16.4
17.7
17.1
16.5
19.8
Gairloch Peninsula
0 2.5 5.0
km
d
Gob a' Gheodha
GA22-14
GA22-12,13
GA22-15
Slaggan Bay
0 100 200
meters

Figure 2.

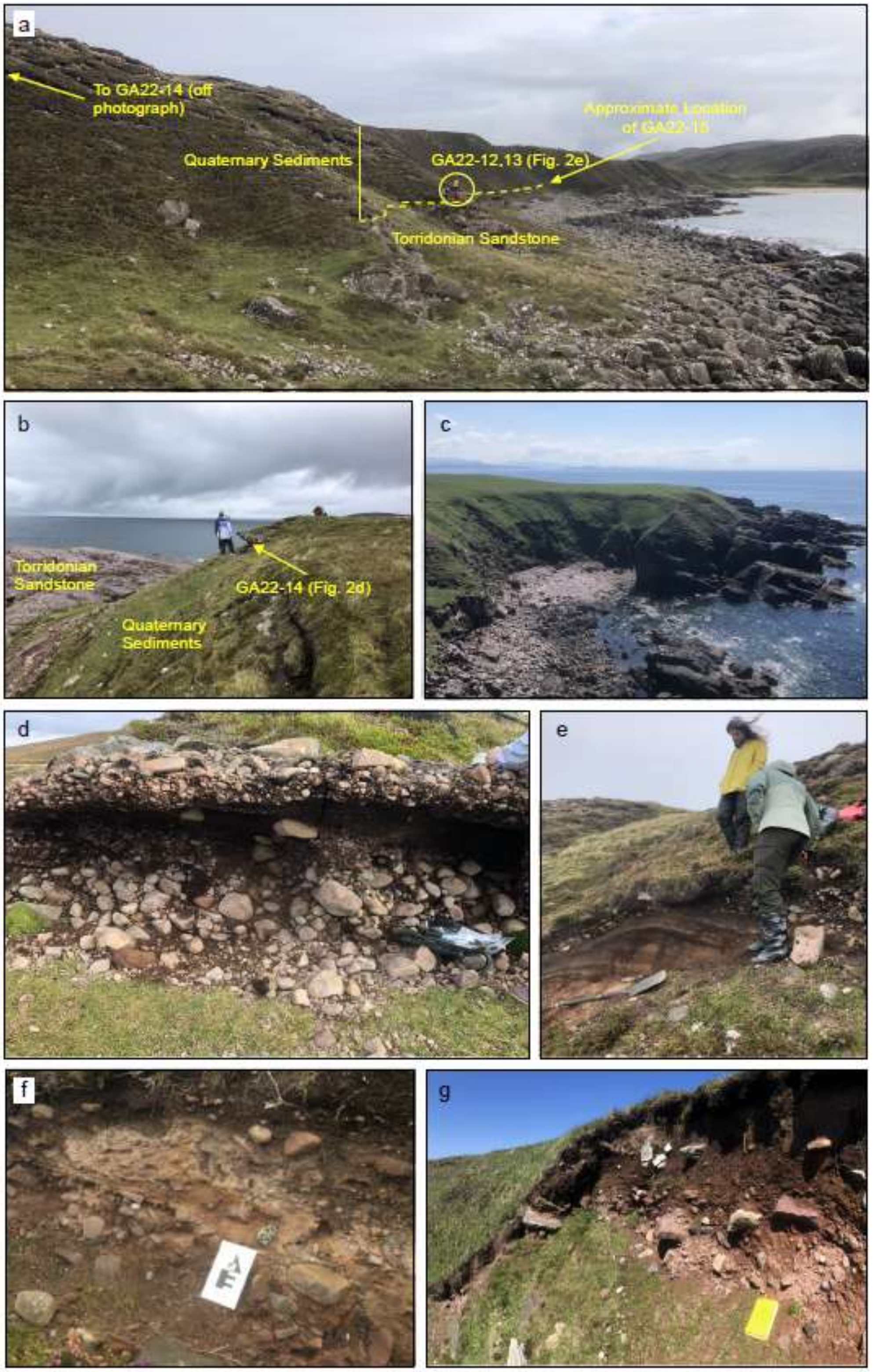
a
To GA22-14 (off photograph)
Approximate Location of GA22-15
Quaternary Sediments
GA22-12,13 (Fig. 2e)
Torridonian Sandstone
b
Torridonian Sandstone
GA22-14 (Fig. 2d)
Quaternary Sediments
c
d
e
f
g

Figure 3.

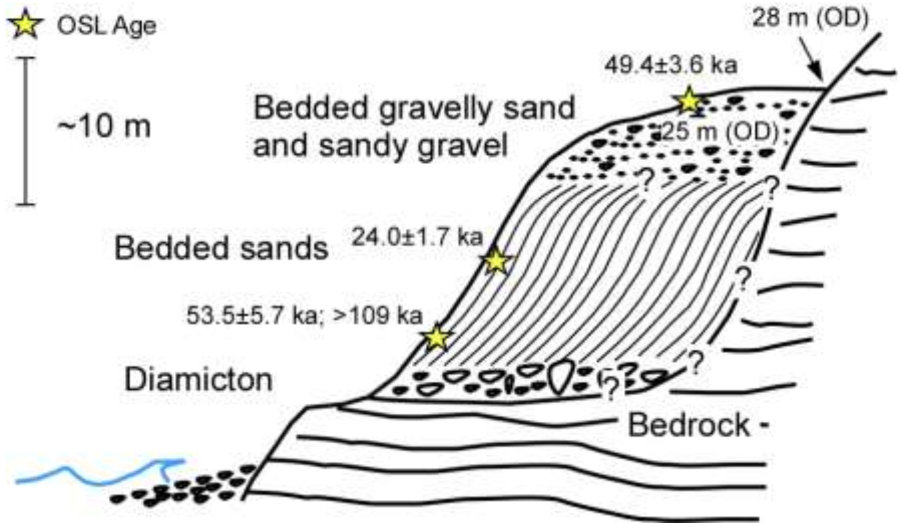
OSL Age
~10 m
28 m (OD)
49.4±3.6 ka
Bedded gravelly sand
and sandy gravel
25 m (OD)
Bedded sands
24.0±1.7 ka
53.5±5.7 ka; >109 ka
Diamicton
Bedrock

Figure 4.

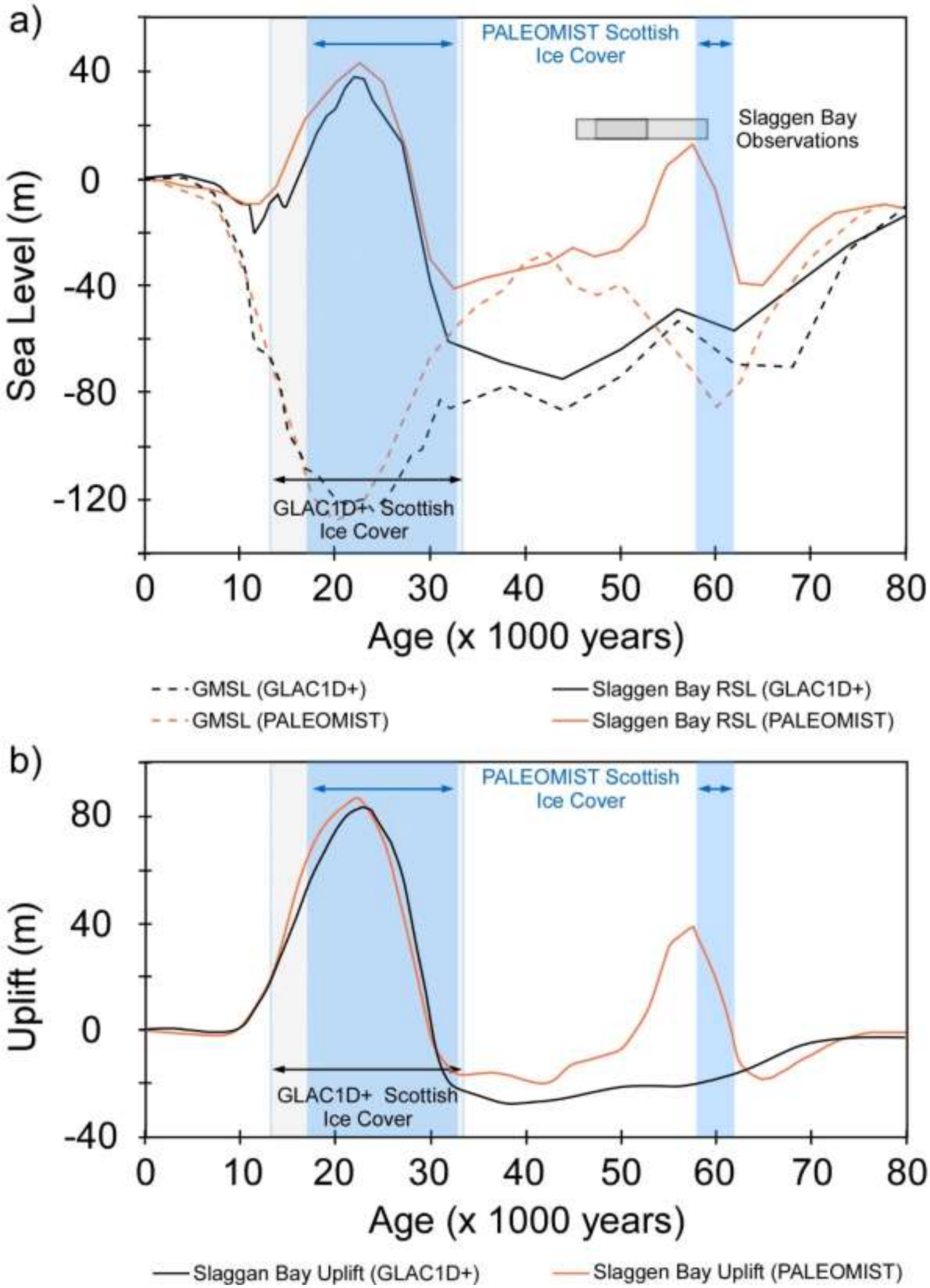
a)
PALEOMIST Scottish
Ice Cover
Slaggen Bay
Observations
GLAC1D+ Scottish
Ice Cover
Sea Level (m)
40
0
-40
-80
-120
0
10
20
30
40
50
60
70
80
Age (x 1000 years)
GMSL (GLAC1D+)
GMSL (PALEOMIST)
Slaggen Bay RSL (GLAC1D+)
Slaggen Bay RSL (PALEOMIST)
b)
PALEOMIST Scottish
Ice Cover
GLAC1D+ Scottish
Ice Cover
Uplift (m)
80
40
0
-40
0
10
20
30
40
50
60
70
80
Age (x 1000 years)
Slaggan Bay Uplift (GLAC1D+)
Slaggen Bay Uplift (PALEOMIST)

Figure S1.

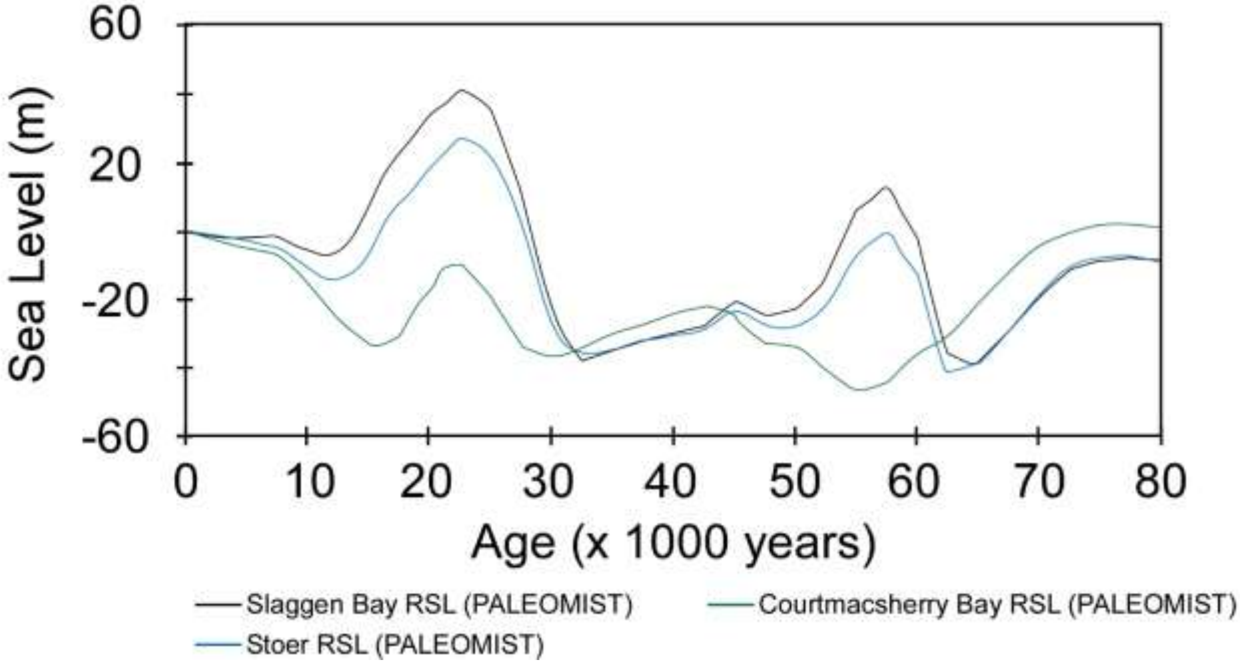

Table 1.

Sample	grain size (µm)	n[†] measured	n[†] used	Dose (Gy)[‡]	overdispersion (%)
GA22-12	150-180	11	11	302.8 ± 22.95[§]	N/A
GA22-13	150-180	29	28	139.1 ± 8.9	18
GA22-14	180-212	41	35	132.9 ± 8.5	20
GA22-15	90-125	30	25	53.3 ± 3.3	12

[†]number of aliquots

[‡]1-sigma uncertainty

[§]Sample GA22-12 was in saturation and the dose reflects the saturation dose of $2D_0$

Table 2.

Sample	Th (ppm)	U (ppm)[‡] from Th234	U (ppm) from Bi214	K (%)	water factor	DR beta (Gy/ka)	DR Gamma (Gy/ka)	DR cosm (Gy/ka)	DR total (Gy/ka)
GA22-12[§]						1.881 ± 0.090	0.798 ± 0.029	0.0957 ± 0.0048	2.774 ± 0.094
GA22-13[§]						1.763 ± 0.221	0.758 ± 0.035	0.0811 ± 0.0041	2.602 ± 0.224
GA22-12[†]/13 g1	3.81 ± 0.35	1.73 ± 0.36	0.800 ± 0.049	2.33 ± 0.11	0.06 ± 0.01				
GA22-12/13 g2	4.96 ± 0.37	1.61 ± 0.34	1.057 ± 0.059	2.42 ± 0.12	0.15 ± 0.03				
GA22-12/13[†] g3	3.82 ± 0.29	1.78 ± 0.31	0.842 ± 0.055	2.14 ± 0.10	0.05 ± 0.01				
GA22-12/13 g4	3.22 ± 0.28	1.94 ± 0.33	0.711 ± 0.048	2.05 ± 0.10	0.08 ± 0.01				
GA22-14						1.747 ± 0.088	0.739 ± 0.027	0.2045 ± 0.0102	2.690 ± 0.092
GA22-14 g1[†]	3.51 ± 0.27	2.15 ± 0.33	0.695 ± 0.044	2.10 ± 0.10	0.05 ± 0.01				
GA22-14 g2	4.87 ± 0.47	1.52 ± 0.40	0.959 ± 0.068	2.31 ± 0.11	0.02 ± 0.01				
GA22-15						1.465 ± 0.080	0.681 ± 0.015	0.0694 ± 0.0035	2.216 ± 0.082
GA22-15 g1	3.65 ± 0.33	0.72 ± 0.19	0.650 ± 0.048	1.75 ± 0.09	0.08 ± 0.01				
GA22-15 g2[†]	4.79 ± 0.41	0.56 ± 0.13	0.857 ± 0.057	1.94 ± 0.09	0.15 ± 0.03				
GA22-15 g3	4.46 ± 0.38	1.18 ± 0.21	1.212 ± 0.078	1.77 ± 0.09	0.00 ± 0.01				

Nuclide concentrations and water contents are listed for each of the separate layers. [†]The layer from which the OSL sample was collected.
[‡]Uranium concentrations obtained from the 92keV emission of Th234 as well as the concentrations obtained from the emissions of Bi214 and Pb214.
[§]Samples GA22-12 and GA22-13 were taken from the same site, but different layers.