Implications of ^{36}Cl exposure ages from Skye, northwest Scotland for the timing of ice stream deglaciation and deglacial ice dynamics.

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Abstract

Constraining the past response of marine terminating ice streams during episodes of deglaciation provides important insights into potential future changes due to climate change. This paper presents new ^{36}Cl cosmic ray exposure dating from boulders located on two moraines (Glen Brittle and Loch Scavaig) in southern Skye, northwest Scotland. Ages from the Glen Brittle moraines constrain deglaciation of a major marine terminating ice stream, the Barra-Donegal Ice Stream that drained the former British-Irish Ice Sheet, depending on choice of production method and scaling model this occurred 19.9 ± 1.5 - 17.6 ± 1.3 ka. We compare this timing of deglaciation to existing geochronological data and changes in a variety of potential forcing factors constrained through proxy records and numerical models to determine what deglaciation age is most consistent with existing evidence. Another small section of moraine, the Scavaig moraine, is traced offshore through multibeam swath-bathymetry and interpreted as delimiting a later stillstand/readvance stage following ice stream deglaciation. Additional cosmic ray exposure dating from the onshore portion of this moraine indicate that it was deposited 16.3 ± 1.3 - 15.2 ± 0.9 ka ago. When calculated using the most up-to-date scaling scheme this time of deposition is, within uncertainty, the same as the timing of a widely identified readvance, the Wester Ross Readvance, observed elsewhere in northwest Scotland. This extends the area over which this readvance is potentially occurred, reinforcing the view that it was climatically forced.

1. Introduction

Concerns over the stability of the remaining ice sheets have been raised by suggestions that irreversible collapse of some marine based sectors is possible or has already begun, with attendant effects on associated terrestrial glaciers (Joughin et al., 2014; Wouters et al., 2015). Marine terminating ice streams are important components of the interconnected ocean-cryosphere system because they discharge large volumes of ice directly into the ocean through calving (Alley and MacAyeal, 1994; Bradwell and Stoker, 2015; Deschamps et al., 2012). While modern observations provide useful information, the temporal coverage is not sufficient to capture the complete response of a marine terminating ice stream to rapid climate change. Researchers are therefore increasingly drawn to analogous palaeo-settings where the complete deglaciation record can be observed (Serjup et al., 2000; Dowdeswell et al., 2014; Svendsen et al., 2015).

Of the Pleistocene ice sheets, the British-Irish Ice Sheet (BIIS) provides a useful analogue. Its western margin was marine terminating while its position next to a major surficial artery of the Atlantic Meridionial Overturning Circulation (AMOC) rendered it potentially sensitive to small climatic perturbations (Knutz et al., 2007). This sensitivity is captured in proxy data (Scourse et al., 2009; Hibbert et al., 2010) and numerical modelling experiments (Hubbard et al., 2009). Past reconstructions of the BIIS relied heavily on onshore mapping of landforms that can be inferred to represent former ice limits including terminal, lateral and recessional moraines (Sissons et al., 1973; Ballantyne, 1989, Bennett and Boulton, 1993; Clark et al., 2004). Recent advances in offshore geomorphological mapping, particularly the use of bathymetric and seismic data, have allowed workers to identify sediments and landforms associated with ice extending onto the continental shelf (Bradwell et al., 2008a; Dunlop et al., 2010; Ò'Cofaigh et al., 2012). This has allowed delimitation of fast flowing ice streams that drained much of the western sector of the former BIIS (Scourse et al., 2000; Stoker and Bradwell, 2005; Howe et al., 2012; Bradwell and Stoker, 2015; Dove et al., 2015). Further identification of subsequent landforms associated with confined ice flow casts light on post-ice streaming behaviour inshore of the onset zone of the BDIS (Howe et al., 2012; Dove et al., 2015).

The Barra-Donegal Ice Stream (BDIS) drained a large portion of the western BIIS and, at the Last Glacial Maximum (LGM), reached the shelf edge (Knutz et al., 2001) where it deposited glaciogenic sediments in the Barra-Donegal Fan (BDF), the southernmost glaciogenic fan on the Eurasian continental margin (Figure 1). Recent observations using swath bathymetry have revealed a suite of glaciogenic landforms at the bed of the former BDIS, stretching from Skye in the north to Islay in the south (Howe et al., 2012; Dove et al., 2015). The BDIS flowed southwest from the Inner Hebrides before turning west around the Outer Hebrides towards the outer shelf (Howe et al., 2012). Large scale erosional features such as glacially over-deepened basins and streamlined bedrock are observed across large areas of the BDIS and provide important information on past ice flow directions. In comparison, large moraines are confined to the mid-outer shelf with smaller recessional moraines being more abundant in the nearshore (Dunlop et al., 2010; Dove et al., 2015).

Offshore evidence from ice rafted detritus (IRD) demonstrates that ice sourced in Scotland reached the shelf edge by 29 ka with a significant reduction in IRD delivery after 23 ka (Knutz et al., 2001; Scourse et al., 2009; Hibbert et al., 2010). To the north, basal marine radiocarbon ages show deglaciation of mid-shelf (Figure 1; Table 1) prior to 16.7 ± 0.3 ka (Peacock et al., 1992; Austin and Kroon, 1996; Small et al., 2013) while cosmogenic exposure and radiocarbon ages (Figure 1) show initial deglaciation of the southern sector of the BDIS before ~20.0 ka (McCabe et al., 2003; Clark et al., 2009). Complete deglaciation of the southern sector occurred before 16.8 ka (Figure 1) (Ballantyne et al., 2014), an inference supported by IRD evidence that the BIIS maintained calving margins throughout the period 23.0-16.0 ka (Scourse et al., 2009, Small et al., 2013). All available geochronological data related to the BIIS was synthesised to produce 1 ka time-slices of the pattern of deglaciation (Clark et al., 2012), this was subsequently refined to include maximum and minimum ice-extents at the same temporal resolution (Hughes et al., 2016). In the BDIS sector both reconstructions depict initial deglaciation from the shelf edge at c.25 ka with ice persisting on the mid-shelf until 19-17 ka. Rapid deglaciation occurs 17-16 ka by which time is located near the present day coastline (Figure 1).

While the submarine geomorphology and retreat pattern of the BDIS is relatively well established (Howe et al., 2012; Dove et al., 2015), post-ice streaming behaviour and geochronological data relating to deglaciation of the northern sector of the BDIS is still comparatively limited. In northwest Scotland a regional scale readvance, the Wester Ross readvance has been delimited from a suite of onshore moraines and dated with ^{10}Be exposure ages to ~ 16 ka (Robinson and Ballantyne, 1979; Bradwell et al., 2008; Ballantyne et al., 2009). However to date, this readvance has not been identified south of Skye. In this contribution we present bathymetric data from inshore waters near Skye, which highlights ice dynamics following ice stream retreat. Cosmogenic ^{36}Cl cosmic ray exposure (CRE) ages from moraine boulders provide geochronological constraints on the timing of this deglaciation.

2. Study Site

Skye is located off the west coast of Scotland, >200 km upstream from the maximum extent of the BDIS at the shelf break (Figure 1). During the LGM the mountains of central Skye (the Cuillin) nourished an independent ice dome, the Skye Ice Dome (SID), which deflected ice moving from the mainland to the west and acted as an ice divide between the BDIS and the Minch Ice Stream (MIS). Together, these ice streams drained the majority of the northern sector of the BIIS (Bradwell et al., 2008a). To the north of Skye, the zone of confluence between mainland ice and the SID is inferred to follow the narrow straits between Skye and the islands of Scalpay and Raasay (Harker, 1901) (Figure 2). To the south, mainland erratics occur on the island of Soay and the orientation of striae on the southern margin of the Cuillin suggest that locally nourished ice was strongly deflected westwards by mainland ice. This implies that the zone of ice confluence lay between Skye and the neighbouring island of Soay (Ballantyne et al., 1991). The southern branch of mainland ice, along with ice flowing south from the Cuillin, fed the embryonic BDIS with ice stream onset beyond Rum (Howe et al., 2012; Dove et al., 2015). The northern branch fed the MIS (Stoker and Bradwell, 2005). Given its central position within the BDIS, Skye is an important location for constraining deglaciation of the BDIS and comparing the deglacial history of neighbouring ice streams that drained a dynamic, marine-based ice sheet.

Deglaciation of the MIS is constrained by several CRE ages. Two ^{36}Cl CRE ages from ice smoothed bedrock on a col in Trotternish (Figure 2) show deglaciation at altitude in Northern Skye before ~16 ka (Stone et al., 1998). Further constraint on final deglaciation of the MIS is provided by five ^{10}Be CRE ages with a mean age of 15.9 ± 1.0 ka from a boulder moraine at Strollamus (Small et al., 2012), above the strait that separates Skye from Scalpay (Figure 2). In contrast, the only CRE ages from southern Skye are from a moraine related to the later Loch Lomond Readvance (LLR) (Small et al., 2012).

Our study focuses on two locations in Southern Skye where there are moraines outside the well mapped LLR limits., Glen Brittle to the west of the Cuillin, and Loch Scavaig, to the south (Figures 2 and 5). At both sites the moraines represent the innermost pre-LLR limit yet identified but without geochronological control it is not possible to determine if they were deposited contemporaneously. In lower Glen Brittle the up-valley termination of raised shorelines coincides with a series of low moraine ridges littered with basalt boulders which have been interpreted as terminal moraines (Walker *et al.,* 1988). These moraines occur well outside the mapped limits of the LLR (Ballantyne, 1989) and thus clearly pre-date them (Figure 3). In Glen Brittle there are two main parallel moraine ridges up to 100 m long and 2-3m high (Figure 3). The ridges are separated by ~50 m.

On Soay which forms the western margin of Loch Scavaig, a small section of moraine comes onshore at the northeastern corner of the island (Clough and Harker, 1904). This moraine section is ~200-300 m in length and 4-5 m high in places. Large erratic gabbro boulders are found on its crest indicating that at some time following deglaciation of the BDIS ice sourced from the Cuillin extended into Loch Scavaig and reached Soay which itself is composed entirely of Torridonian sandstone with some Tertiary basalt dykes.

3. Methods

3.1 Bathymetry

To constrain deglaciation of the BDIS we confirmed the presence of ice margin positions in southern Skye from onshore fieldwork in Glen Brittle and a bathymetric survey of Loch Scavaig. This study used a SEA SwathPlus High Frequency System with a central frequency of 468 kHz and a ping rate of up to 30 pings per second giving a potential footprint of less than 5 cm at standard survey speed. Data were acquired with a TSSDMS205 motion reference unit and positioning provided by a Topcon Hiper RTK dGPS. The RTK dGPS base system was established on the loch shore and tied to the BNG datum using Rinex corrections from the OS. An Applied Microsystems MicroSV sound velocity probe was mounted at the sonar head in order to record changes in velocity due to mixing of different waters (and thus potential salinity changes) in the relatively enclosed waters of the loch. Final data were recorded to a position accuracy of better than +/-5 cm, however the final data set was processed to a bin resolution of 2 m with vertical heights given to ± 20 cm. The data was processed using SwathPlus and GridProcessor (SEA Ltd) with further editing using IVS Fledermaus. Bathymetric data points were converted from WGS84 to OSGP using the OSGB36 datum (origin 49°N and 2°W). Final data processing was accomplished within ArcGIS (v10).

3.2 Surface exposure dating using ^{36}Cl.

3.2.1 Sampling

Moraines with suitable material for CRE dating using *in situ*-produced cosmogenic ^{36}Cl were identified in Glen Brittle and on the island of Soay where the onshore continuation of an offshore moraine is located. Eleven samples, four from Glen Brittle and seven from Soay, were collected from basic igneous boulders (basalt and gabbro) for CRE dating. In Glen Brittle two samples were collected from the outer moraine ridge (BRI01 and BRI04) and two samples from the inner moraine ridge (BRI02-03). On Soay 7 samples were collected from the onshore moraine section (Figure 4).

We selected boulders from moraine crests with the largest *b*-axis to minimise the potential for disturbance and snow cover. Where possible we sampled sub-rounded boulders considered indicative of sub-glacial transport (Ballantyne and Stone, 2009) to minimise the potential for inheritance. Similarly we sampled boulders with intact top surfaces as they are least likely to have suffered significant chemical weathering and to minimise the potential influence of spallation of material Samples were collected from the top surfaces of boulders using hammer and chisel. When possible, we sampled flat surfaces but, where necessary, strike and dip were recorded using a compass-clinometer. Detailed site descriptions (e.g. geomorphological context, boulder dimensions, weathering) were made for each sample. Sample locations and elevations were recorded using a hand-held GPS with elevations checked against 1:25000 maps. Skyline measurements were taken using a compass-clinometer at all sites with the topographic shielding factors calculated using the skyline calculator within the CRONUS online calculator (Balco et al., 2008; http://hess.ess.washington.edu/math/general/skyline_input.php; accessed on 14th September 2015). Sample information is shown in Table 2. Sample photos are shown in Figures 5 (Glen Brittle) and 6 (Soay).

3.2.2 Processing

The thickness and dry bulk density of samples from each site was measured before samples for ^{36}Cl analysis were crushed and sieved to 250-500 µm at the University of St Andrews. About 2 g of material was retained for elemental analysis with the remainder sent to University of New Hampshire for further preparation and isotopic extraction. Chlorine was extracted and purified from whole-rock samples to produce AgCl for accelerator mass spectrometry (AMS) analysis, following a modified version of procedures developed by Stone et al. (1996). Crushed samples were sonicated first in distilled water and then in 2% HNO_3 to remove any secondary material attached to grains. 13-20 g of pretreated rock was prepared from each sample for subsequent chemical procedures. Samples were spiked with ~0.48 g of isotopically enriched carrier ($^{35}Cl/^{37}Cl = 999 \pm 4$, total Cl concentration = 3.65 mg g^{-1}) before dissolution in an HF – HNO_3 solution. Following complete dissolution, aqueous samples were separated from solid fluoride residue by centrifuging, and ~1 ml of 5% $AgNO_3$ solution was added to precipitate AgCl (and Ag_2SO_4 if sulfates were present). The precipitate was collected by centrifuging and dissolved in NH_4OH solution. To remove sulfates, ~1 ml of saturated $(BaNO_3)_2$ was added to precipitate $BaSO_4$. Final precipitation of AgCl from the aqueous solution was accomplished by addition of 2 M HNO_3 and 5% $AgNO_3$. The final AgCl precipitate was collected by centrifuging, washed repeatedly with 18.2 MΩ-cm deionized water, and dried. Approximately 1.5 – 1.75 mg of purified AgCl target material was produced from each sample for AMS measurement.

3.2.2 Analysis and age calculations

^{36}Cl measurements were carried out at the 5 MV French accelerator mass spectrometry national facility ASTER at CEREGE (Arnold et al., 2013). Use of an isotopically enriched carrier allows simultaneous measurement of $^{35}Cl/^{37}Cl$ and determination of the natural Cl content of the dissolved samples. For normalization of $^{36}Cl/^{35}Cl$ ratios, calibration material 'KN1600' prepared by K. Nishiizumi, was used. This has a given $^{36}Cl/^{35}Cl$ value of 2.11 ± 0.06 x 10^{-12} (Fifield et al., 1990). Typical uncertainties for raw AMS data are 0.3 – 1.2% for $^{35}Cl/^{37}Cl$ and 4.8 – 8.0% for $^{36}Cl/^{35}Cl$. All samples have $^{36}Cl/^{35}Cl$ ratios in the range of 3.8 – 6.9 x 10^{-14} compared to two process blanks (CLBLK7 & 8) with $^{36}Cl/^{35}Cl$ ratios of 7.83 ± 1.0 and 4.15 ± 0.75 x 10^{-15}, respectively. Resulting blank corrections therefore range between 3.4 and 18.1%. Measurement results and calculated concentrations with uncertainties are shown in Table 3.

^{36}Cl CRE ages were calculated using the CRONUScalc online calculator (http://web1.ittc.ku.edu:8888; accessed 09/02/2016; Marrero et al., 2016a) and a freely available spreadsheet (Schimmelpfennig et al., 2009). ^{36}Cl production rates for spallation (Ca, K) have recently been updated by Marrero et al. (2016b). Consequently, we calculated our exposure ages using sea level-high latitude ^{36}Cl production rates of 56.0 ± 4.1, 155 ± 11, 13 ± 3 and 1.9 ± 0.2 atoms ^{36}Cl g^{-1} a^{-1}, for Ca, K, Ti and Fe, respectively (Marrero et al., 2016b; Schimmelpfennig et al., 2009). In comparison, previous production rates for Ca and K were 42.2 ± 4.8, 145.5 ± 7.7 atoms $^{36}Cl\ g^{-1}\ a^{-1}$ (Schimmelpfennig et al., 2011, 2014; also see Braucher et al., 2011). We report CRE ages calculated using both Ca and K production rates and scaled for latitude and altitude according to Stone (2000), as adapted by Balco et al. (2008), and Lifton et al. (2014) for comparison. CRE ages were calculated assuming no erosion. Correcting for 1 mm ka^{-1} erosion would vary exposure ages by 1-2%. The chemical composition of representative bulk material was determined for each individual sample at the Facility for Earth and Environmental Analysis at the University of St Andrews using X-ray fluorescence (XRF) for major elements and inductively coupled plasma mass spectrometry (ICP-MS) for minor and trace elements. The composition of individual samples is shown in Table 4.

3.3 Comparison to proximal marine cores:

We compare our surface exposure dating of the marine terminating Barra-Donegal Ice Stream with two proximal marine records, MD02-2822 (Hibbert, 2011; Hibbert et al., 2010) and MD01-2461 (Peck et al., 2006, 2008). Giant piston core MD04-2822 was recovered by the RV *Marion Dufresne* from the deep-water margins of the BDF in the Rockall Trough (Figure 1; 56° 50.54’ N, 11° 22.96’ W; 2344 m water depth, recovered in 2004). MD01-2461 was collected from the north-western flank of the Porcupine Seabight approximately 550 km to the southwest (51°45’N, 12°55’W; 1153 m water depth, recovered in 2001). This region lies within the zone of meridional oscillation of the North Atlantic Polar Front during the last glacial (Knutz et al., 2007; Scourse et al., 2009; Hibbert et al., 2010) and as a result is ideally positioned to record both the prevailing hydrographic conditions and the dynamics of the proximal BIIS.

Each core is plotted on their own age model based on tuning to the Greenland $\partial^{18}O$ ice core records (using NGRIP on the GICC05 timescale for MD04-2822 and GISP2 for MD01-2461) and calibrated ^{14}C dates (Figure 10). We have updated the age model for MD04-2822 using: the most recent calibration dataset (IntCal13; Reimer et al., 2013); age uncertainty estimates for each tie-point (a mean squared estimate incorporating uncertainties from both the ice core chronology and tuning procedure) and; a Bayesian deposition model (OxCal 'Poisson' function; Bronk Ramsey and Lee, 2013) (Supplementary Table 1).

4. Results

4.1 Multibeam bathymetry

The multibeam bathymetric survey of Loch Scavaig reveals numerous features – both glaciogenic and post glacial – of interest. The most conspicuous of these is a large arcuate ridge that spans Loch Scavaig and connects with the observed onshore moraine section found on Soay. The ridge is ~4.5 km long and up to 10 m high in places (Figures 7 and 8). A further small extension (~1 km) of this ridge crosses the Sound of Soay to come onshore on the southern margin of the Cuillin. This ridge is interpreted as a terminal moraine, the Scavaig moraine, that clearly delimits the extent of a glacier that flowed from the central rock basin of the Cuillin and into Loch Scavaig.

The glacial land-system preserved in Loch Scavaig is very different, both in morphology and scale, from that associated with surging tidewater glaciers in Svalbard (Ottesen et al., 2008) with a lack of megascale glacial lineations, crevasse fills and eskers. In addition, the scale and shape of the Scavaig moraine is strikingly different from thrust moraines in Svalbard, which are up to 1 km across with large debris flow lobes on their distal slopes (Ottesen et al., 2008; Kristensen et al., 2009). The Scavaig moraine is a much smaller feature with a well-defined crest, it is generally arcuate in planform, with an asymmetric profile. These features are consistent with a push moraine formed at the margin of the former glacier, indicating that the Scavaig moraine was not formed by a surging glacier but instead marks a readvance of ice from the Cuillin or a still-stand during overall retreat. The Scavaig moraine is traceable across the floor of Loch Scavaig and onto the island of Soay (Figure 4 and 8). The onshore section aligns exactly with the offshore moraine, is composed of material from the Cuillin where the glacier that deposited the Scavaig moraine must have been sourced. It is therefore clearly part of the same feature.

Within the limits of the large moraine is a suite of shorter but conspicuous linear ridges, most prominent in the east of the survey area and immediately inboard of the large moraine (Figure 8). These are up to 2 km long and 5 m high and are interpreted as recessional moraines formed during deglaciation from the outer limit demarked by the Scavaig moraine.

In the east of the survey area, an area of the sea floor is covered with chaotic, hummocky topography (Figure 8). This bears resemblance to features identified as submarine slope failures in bathymetric studies carried out elsewhere in Scotland (Stoker et al., 2010). In addition, the features occur immediately below a conspicuous failure scarp that occurs on Ben Cleat which forms the eastern shore of Loch Scavaig. This feature is interpreted as a post-glacial rock slope failure. Similar terrestrial features in Scotland have been linked to glacial debuttressing and seismic activity associated with post-glacial isostatic rebound (Ballantyne and Stone, 2013).

4.2 Surface exposure dating using ^{36}Cl.

The exposure ages calculated following Schimmelpfennig et al. (2009) and Marrero et al., (2016a, b) are shown in Table 5. Due to the differing ways in which each calculator deals with the numerous production pathways of ^{36}Cl and the varying compositions of our samples the difference in calculated CRE age is not consistent between samples although the ages calculated using the Lm scaling show general agreement between the Schimmelpfennig calculator (Schimmelpfennig et al., 2009) and CRONUScalc (Marrero et al., 2016a). Notably, the choice of scaling is important when using the new CRONUScalc online calculator with CRE ages calculated using the Lm scaling (Stone et al., 2000; Balco et al., 2008) being up to 14% older than when calculated with the SA scaling (Lifton et al., 2014). The cause of this discrepancy is currently enigmatic. The dependency of the CRE ages on choice scaling scheme makes interpretation difficult as there is the danger of selecting CRE ages to fit pre-existing or favoured hypotheses. However, given the range of production rate calibrations included in the CRONUScalc programme, the improved agreement with observed atmospheric cosmic-ray fluxes obtained using the SA scaling scheme and for simplicity, we focus discussion on CRE ages calculated using CRONUScalc and the SA scaling. We present the alternative CRE age calculations for completeness.

The ^{36}Cl CRE ages range from 19.4 ± 1.7 to 12.9 ±1.2 ka. The Glen Brittle samples (BRI-01-04) yield CRE ages between 19.4 ± 1.7 and 15.5 ± 1.7 ka while the Soay samples (SOAY-1-7) yield CRE ages between 16.4 ± 1.5 and 12.9 ± 1.2 ka. A plot of all ^{36}Cl CRE ages reveals significant overlap in ages from both locations (Figure 9, Table 5). The 11 samples combined have a reduced Chi-square (χ^2_R) = 4.51 indicating that they are not a single population and are influenced by geological uncertainty. Additionally, a Student's *t* test ($p < 0.01$) suggests that the CRE ages from the two valleys are significantly different. Given this, and the absence of direct geomorphological correlation between the sampled moraines in Glen Brittle and Soay we consider each sample site individually. The Glen Brittle samples have $\chi^2_R = 1.59$ which is an acceptable value for a population with three degrees of freedom (Bevington and Robinson, 2003).

The Soay samples have $\chi^2_R = 2.06$ indicating the CRE ages are not a single population. Figure 9 shows two CRE age clusters at ~13 ka and ~15 ka ($\chi^2_R = 0.02$ and 0.05, respectively). There are two potential interpretations of these CRE ages. The first is that the younger CRE age population reflects the age of deposition of the Scavaig moraine and that the older CRE ages reflect nuclide inheritance from a previous exposure. An alternative interpretation is that the older CRE ages are representative of the true moraine age and the young CRE ages are the result of some post-depositional adjustment and/or exhumation.

5. Discussion

5.2 Time of moraine deposition

A compilation of exposure ages from boulders suggests that they are more likely to underestimate the true CRE age (Heyman et al., 2011). However, this compilation was solely comprised of ^{10}Be CRE ages. The greater importance of muons in ^{36}Cl production (e.g. Stone et al., 1998; Braucher et al., 2013) means ^{36}Cl CRE ages have a greater propensity for inheritance and thus overestimation of ages. Similarly the more complicated evolution of production rate with depth (cf. Gosses and Philips, 2001) means that erosion and or spalling of boulder surfaces can make CRE ages appear older than the true boulder age. Despite careful sample selection (Section 3.2.1) the spread in our ages demonstrates that some of our samples were influenced by geological uncertainty. We therefore outline what ages we believe best represent the true moraine age and use these ages as the basis for our interpretation with a general note of caution that our ages may overestimate the true moraine age. We outline some reasons why we consider this less likely however acknowledge it as a possibility.

Given the agreement between the CRE ages from Glen Brittle we consider an arithmetic mean to best represent the timing of moraine deposition. Thus we infer that the Glen Brittle moraines were most likely deposited at 17.6 ± 1.3 ka, the mean of our ages. At this time relative sea level (RSL) around the south coast of Skye was high (Figure 11) and the termination of high shorelines is associated with the dated moraines in Glen Brittle. This led Walker et al. (1988) to speculate that at the time of high RSL ice occupied Glen Brittle, a view supported by our CRE ages. We note that there is considerable spread in the ages from Glen Brittle and that the mean age may over- or underestimate the true moraine age.

As stated in section 4.2 there are two possible interpretations of the exposure ages from Soay. We consider it unlikely that nuclide inheritance would affect the other boulders to the same degree such that they yielded internally consistent CRE ages that give an acceptable χ^2_R value. Additionally, the young CRE ages suggest moraine deposition prior to the LLR (≈ Younger Dryas - 12.9–11.7 ka b2k; Lowe et al., 2008). This would imply ice survival throughout the warm Bølling-Allerød interstadial, a scenario that is considered unlikely in Scotland (Ballantyne and Stone, 2012). If the older CRE age cluster is to be inferred as best representing the true moraine age it does however raise the question of how the three other boulders were exhumed at the same time. We note that these three boulders are located in very close proximity (Figure 4) and that in comparison to the other sampled boulders they are relatively low lying. Boulder height has been shown to influence the clustering of CRE ages with taller boulders being favoured over shorter boulders (Heyman et al., 2016). Thus while we cannot speculate on the specific mechanism of exhumation the boulder-height relationship identified by Heyman et al. (2016) and the close spatial proximity of the three young Soay samples suggests that contemporaneous exhumation is possible. Given all of these considerations, we favour the second scenario and infer that the Scavaig moraine was most likely deposited 15.2 ± 0.9 ka.

The mean ages from the moraines do not agree within their analytical uncertainties which, given the proximity of the sample locations, suggests that they may represent separate glacial events. However, we note that there is considerable overlap between the ages from Glen Brittle and Soay thus we can not definitively make this conclusion. We therefore propose, as a hypothesis, that two separate readvances occurred on the southern margin of the SID during deglaciation. This hypothesis requires further testing with geochronological data.

5.1 Implications for local ice dynamics

Evidence for readvance of locally nourished ice on Skye has been documented from several localities on the low ground that surrounds the Cuillin (Benn, 1997). Glacio-tectonised sediments, patterns of erratic dispersal and changes in the marine limit, all suggest that locally nourished ice remained dynamically active after its separation from mainland ice. Benn (1997) delimited potential readvance limits of the SID, but whether these were contemporaneous has, thus far, remained untested.

It has previously been suggested that readvance of the SID may have resulted from the removal of constraints imposed by confluent ice allowing the ice to drain radially away from the high ground (Benn, 1997). To the north of the SID a readvance/stillstand is inferred from ice-thrust subaqueous outwash at Suisnish in southern Raasay (Benn, 1997). This site is likely to have been proximal to an ice margin when the Strollamus moraine was deposited at 15.9 ± 1.0 ka (Small et al., 2012). This similarity in age to the older CRE exposure ages from Soay suggests that readvance of the northern and southern sectors of the SID may have been synchronous within dating uncertainties. Additionally, the CRE ages of the Scavaig moraine from Soay and the ^{10}Be CRE ages from the Strollamus moraine are the same as a suite of ^{10}Be CRE ages from moraines delimiting the Wester Ross Readvance (Figure 2), ~60 km to the northwest (Robinson and Ballantyne, 1979; Bradwell et al., 2008b, Ballantyne et al., 2009). While the Strollamus moraine has been interpreted as a medial moraine and thus does not record a readvance, it does indicate the existence of a significant ice mass at the time of the WRR. If the Scavaig moraine represents a later readvance, or our CRE ages overestimate the age the Glen Brittle moraine, then, in combination with the evidence for readvance at Suisnish, it is possible that the Wester Ross Readvance may have been more widespread than previously recognized, and involved readvance of local ice on Skye. If this is the case then it implies a common, and likely climatic trigger such as an increase in precipitation associated with climatic warming (c.f. Ballantyne and Stone, 2012). We note however that the uncertainties associated with our ages prevent definitive correlation of the Scavaig moraine to moraines dated elsewhere in Scotland.

5.2 Deglaciation of the BDIS

The deposition age of the Glen Brittle moraine provides a constraint on final deglaciation of the BDIS as its morphology and lithology demonstrates deposition by valley glaciers fed from the locally nourished SID. As such, it would not be possible to form moraines in Glen Brittle until BDIS deglaciation was complete. Taken at face value, the ^{36}Cl CRE ages from Glen Brittle presented here suggest deglaciation of the northern sector of the BDIS had occurred by 17.6 ± 1.3 ka (SA scaling). Use of the Lm scaling makes deglaciation considerably earlier (19.9 ± 1.1 ka) although the ages do overlap at

1σ. Considered alongside existing geochronological control from the north coast of Ireland and Jura (McCabe and Clark, 2003; Clark et al., 2009; Ballantyne et al., 2014) (Figure 1), our data suggest that the entire marine portion of the former BDIS was deglaciated by 17.6 ± 1.3 ka. Notably, this timing of deglaciation compares well to a reduction in delivery of IRD to the adjacent deep-sea core MD04-2822 (Hibbert et al., 2010) (Figure 10G). Previous reconstructions of the BIIS (Clark et al., 2012; Hughes et al., 2016) depict ice persisting on the mid-inner shelf until ~17 ka with ice reaching the coastline at 16 ka. Our data from Glen Brittle suggest that deglaciation occurred earlier and that ice may have reached the coastline several ka earlier than previously inferred. Notably use of the Lm scaling to calculate the CRE age would exacerbate this difference.

Numerous oceanic forcing mechanisms have been linked to observations of marine deglaciation within the palaeoenvironment. Eustatically forced changes in sea-level (ESL) rise has been cited as a potentially important factor in deglaciation of other palaeo-ice streams that drained the BIIS (Scourse and Furze, 2001; Haapaniemi et al., 2010; Chiverrell et al., 2013) and an initial eustatic sea level rise occurs at 19 ka (e.g., DeDeckker and Yokoyama, 2009; Lambeck et al., 2014), prior to BDIS deglaciation at 17.6 ± 1.3 ka, as constrained by our data (Figure B).

Additionally, it has been shown that tidal mechanical forcing can impact on grounded ice streams (Murray et al., 2007; Arbic et al., 2008; Rosier et al., 2015). The palaeotidal regime influencing the western ice streams draining the BIIS was enhanced compared to the present day because the open glacial North Atlantic was characterized by megatidal amplitudes (tidal ranges > 10 m) in many sectors south of the Iceland-Faroe-Scotland ridge (Uehara et al., 2006; Scourse et al., submitted). Hitherto it has been difficult to disentangle the relative influence of tidal amplitudes *vis-à-vis* relative sea level (RSL) changes but recent modelling efforts have addressed this issue for the BIIS (Scourse et al., submitted) and generated simulations of the potential influence of palaeotides on the BDIS (Figure 11). These show an enhanced tidal regime in the period immediately prior to deglaciation as constrained by the CRE ages from Glen Brittle in the inner BDIS sector (Figure 11). This raises the possibility that this mechanism is a potentially important driver of deglaciation. However, these large tidal amplitudes are associated, in this area, with falling RSL driven by rapid glacio-isostatic uplift which will have mitigated the impact of large tidal range on, for instance, calving rates and ice stream velocities. Similarly, the deposition of the Scavaig moraine occurred during a period of enhanced palaeotidal amplitude but falling RSL (Figure 11). The continuity of these RSL and palaeotidal trends throughout deglaciation imply that other factors; e.g. climate, topography, ice sheet internal dynamics; were controlling the higher frequency BDIS advance/readvance phases documented by the new data.

Finally, changes in ocean circulation that allow warmer water to access the calving front (e.g. Holland et al., 2008) have been cited as a major factor in past deglaciations (Marcott et al., 2011, Rinterknecht et al., 2014). Records of Nps% and $\delta^{18}O_{Nps}$ in MD04-2822 and a Mg/Ca sea surface temperature estimate from MD01-2461 (Peck et al., 2008) (Figure 10C, D, E) show a consistent trend indicating northerly migration of the polar front during Greenland Interstadial 2 (GI-2). Scourse et al. (2009) cite this oceanic warming as a driver of a major phase of BIIS deglaciation represented by high IRD fluxes to the deep sea record from ~23 ka. That the BDIS was likely involved in this is indicated by the IRD records from the proximal cores MD95-2006 (Knutz et al., 2001) and MD04-2822 (Hibbert et al., 2010). The rate at which the BDIS deglaciated in response to GI-2 remains unclear. The IRD record from MD04-2822 retains high IRD fluxes 22-18 ka (Hibbert et al., 2010) indicating that the BIIS, and most likely the BDIS, retained calving margins throughout this period. This implies deglaciation may have been a continuous process with punctuated retreat across the shelf although additional geochronological data from the mid-outer shelf is needed to provide further constraints on the nature of BDIS deglaciation in response to GI-2.

6. Conclusions

The data presented here provide insights into the timing of deglaciation of a major palaeo-ice stream that drained a large portion of the former BIIS as well as indicating post-ice stream dynamics of the remnant ice mass. Following de-coupling of ice sourced from mainland Scotland and ice sourced in Skye, our data lead us to hypothesise that there were possibly two local readvances/stillstands at ~17.6 and ~15.2 ka demarked by moraines in Glen Brittle and Loch Scavaig, respectively. Evidence for local readvance of ice sourced in Skye occurs around the periphery of Cuillin and our data suggests that the latter readvance, north and south of the Cuillin, was contemporaneous with the Wester Ross Readvance recorded elsewhere in northern Scotland, strengthening the conclusion that it was climatically forced.

The ^{36}Cl CRE ages from Glen Brittle provide constraints on the timing of final deglaciation of a major ice stream that drained the former BIIS. They indicate that deglaciation of the BDIS was complete by 17.6 ± 1.3 ka, in general agreement with offshore IRD evidence. The complex production pathways associated with *in situ*-produced ^{36}Cl lead to large inherent uncertainties on our data that prevent us from definitively linking deglaciation of the BDIS and subsequent readvance to any one forcing factor. Ultimately, disentangling the relative contribution of the various forcing factors requires further data constraining ice margin retreat on the shelf combined with new and more precise geochronological data that constrains final deglaciation.

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References

Alley, R.B. and MacAyeal, D.R., 1994. Ice‐rafted debris associated with binge/purge oscillations of the Laurentide Ice Sheet. *Paleoceanography*, *9*, 503-511.

Arbic, B.K., Mitrovica, J.X., MacAyeal, D.R. and Milne, G.A., 2008. On the factors behind large Labrador Sea tides during the last glacial cycle and the potential implications for Heinrich events. *Paleoceanography*, *23*, PA3211.

Austin, W.E.N. and Kroon, D., 1996. Late glacial sedimentology, foraminifera and stable isotope stratigraphy of the Hebridean Continental Shelf, northwest Scotland. *Geological Society, London, Special Publications*, *111*, 187-213.

Arnold, M., Aumaître, G., Bourlès, D.L., Keddadouche, K., Braucher, R., Finkel, R.C., Nottoli, E., Benedetti, L. and Merchel, S., 2013. The French accelerator mass spectrometry facility ASTER after 4years: Status and recent developments on ^{36}Cl and ^{129}I. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *294*, 24-28.

Ballantyne. C.K., 1989, The Loch Lomond Readvance on the Isle of Skye, Scotland: glacier reconstruction and palaeoclimatic implications: *Journal of Quaternary Science*, *4*, 95-108.

Ballantyne, C.K., and Stone, J.O., 2012, Did large ice caps persist on low ground in north-west Scotland during the Lateglacial Interstade?: *Journal of Quaternary Science*, *27*, 297-306.

Ballantyne, C.K. and Stone, J.O., 2013. Timing and periodicity of paraglacial rock-slope failures in the Scottish Highlands. *Geomorphology*, *186*, 150-161.

Ballantyne C.K., Benn, D.I., Lowe, J.J., Walker, M.J.C., (Eds.), 1991, The Quaternary of the Isle of Skye: Field Guide, Quaternary Research Association, Cambridge.

Ballantyne, C.K., Schnabel, C. and Xu, S., 2009. Readvance of the last British–Irish ice sheet during Greenland interstade 1 (GI-1): the Wester Ross readvance, NW Scotland. *Quaternary Science Reviews*, *28*, 783-789.

Ballantyne, C.K., Wilson, P., Gheorghiu, D., and Rodés, À., 2014, Enhanced rock-slope failure following ice-sheet deglaciation: timing and causes: *Earth Surface Processes and Landforms*, *39*, 900-913.

Benn, D.I., 1997. Glacier fluctuations in western Scotland. *Quaternary International*, *38*, 137-147.

Bennett, M.R., 2003. Ice streams as the arteries of an ice sheet: their mechanics, stability and significance. *Earth-Science Reviews*, *61*, 309-339.

Bennett, M.R. and Boulton, G.S., 1993. Deglaciation of the Younger Dryas or Loch Lomond Stadial ice-field in the northern Highlands, Scotland. *Journal of Quaternary Science*, *8*, 133-145.

Baltzer, A., Bates, R., Mokeddem, Z., Clet-Pellerin, M., Walter-Simonnet, A.V., Bonnot-Courtois, C. and Austin, W.E., 2010. Using seismic facies and pollen analyses to evaluate climatically driven change in a Scottish sea loch (fjord) over the last 20 ka. *Geological Society, London, Special Publications*, *344*, 355-369.

Berger, A., and Loutre, M.F., 1991, Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews*, *10*, 297-317.

Bevington, PR and Robinson, D.K., 2003, Data reduction and error analysis: McGraw–Hill, New York, p. 320.

Bradwell, T. and Stoker, M.S., 2015. Submarine sediment and landform record of a palaeo-ice stream within the British– Irish Ice Sheet. *Boreas*, *44*, 255-276.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., Everest, J.D., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L. and Finlayson, A.G., 2008a. The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, *88*, 207-226.

Bradwell, T., Fabel, D., Stoker, M., Mathers, H., McHargue, L. and Howe, J., 2008b. Ice caps existed throughout the Lateglacial Interstadial in northern Scotland. *Journal of Quaternary Science*, *23*, 401-407.

Braucher, R., Merchel, S., Borgomano, J. and Bourlès, D.L., 2011. Production of cosmogenic radionuclides at great depth: A multi element approach. *Earth and Planetary Science Letters*, *309*, 1-9.

Clark, C.D., Evans, D.J., Khatwa, A., Bradwell, T., Jordan, C.J., Marsh, S.H., Mitchell, W.A. and Bateman, M.D., 2004. Map and GIS database of glacial landforms and features related to the last British Ice Sheet. *Boreas*, *33*, 359-375.

Clark, C.D., Hughes, A.L., Greenwood, S.L., Jordan, C., and Sejrup, H.P., 2012, Pattern and timing of retreat of the last British-Irish Ice Sheet: *Quaternary Science Reviews*, *44*, 112-146.

Clark, J., McCabe, A.M., Schnabel, C., Clark, P.U., McCarron, S., Freeman, S.P., Maden, C. and Xu, S., 2009. Cosmogenic ^{10}Be chronology of the last deglaciation of western Ireland, and implications for sensitivity of the Irish Ice Sheet to climate change. *Geological Society of America Bulletin*, *121*, 3-16.

Clough, C.T. and Harker, A., 1904. *The Geology of West-Central Skye, with Soay: Explanation of* (Vol. 70). HM Stationery Office.

Chiverrell, R.C., Thrasher, I.M., Thomas, G.S., Lang, A., Scourse, J.D., van Landeghem, K.J., Mccarroll, D., Clark, C.D., Cofaigh, C.Ó., Evans, D.J. and Ballantyne, C.K., 2013. Bayesian modelling the retreat of the Irish Sea Ice Stream. *Journal of Quaternary Science*, *28*(2), pp.200-209.

De Deckker, P. and Yokoyama, Y., 2009. Micropalaeontological evidence for Late Quaternary sea-level changes in Bonaparte Gulf, Australia. *Global and Planetary Change*, *66*, 85-92.

Deschamps, P., Durand, N., Bard, E., Hamelin, B., Camoin, G., Thomas, A.L., Henderson, G.M., Okuno, J.I. and Yokoyama, Y., 2012. Ice-sheet collapse and sea-level rise at the Bolling warming 14,600 years ago. *Nature*, *483*, 559-564.

Dove, D., Arosio, R., Finlayson, A., Bradwell, T. and Howe, J.A., 2015. Submarine glacial landforms record Late Pleistocene ice-sheet dynamics, Inner Hebrides, Scotland. *Quaternary Science Reviews*, *123*, 76-90.

Dowdeswell, J.A., Hogan, K.A., Cofaigh, C.Ó., Fugelli, E.M.G., Evans, J. and Noormets, R., 2014. Late Quaternary ice flow in a West Greenland fjord and cross-shelf trough system: submarine landforms from Rink Isbrae to Uummannaq shelf and slope. *Quaternary Science Reviews*, *92*, 292-309.

Dunlop, P., Shannon, R., McCabe, M., Quinn, R., and Doyle, E., 2010, Marine geophysical evidence for ice sheet extension and recession on the Malin Shelf: New evidence for the western limits of the British Irish Ice Sheet: *Marine Geology*, *276*, 86-99.

Fabel, D., Ballantyne, C.K. and Xu, S., 2012. Trimlines, blockfields, mountain-top erratics and the vertical dimensions of the last British–Irish Ice Sheet in NW Scotland. *Quaternary Science Reviews*, *55*, 91-102.

Fifield, L.K., Ophel, T.R., Allan, G.L., Bird, J.R. and Davie, R.F., 1990. Accelerator mass spectrometry at the Australian National University's 14UD accelerator: experience and developments. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *52*, 233-237.

Haapanieni, A.I., Scourse, J.D., Peck, V.L., Kennedy, D.P., Kennedy, H., Hemming, S.R., Furze, M.F.A., Pieńkowski-Furze, A.J., Walden, J., Wadsworth, E. and Hall, I.R. 2010. Source, timing, frequency and flux of ice-rafted detritus to the Northeast Atlantic margin, 30-12 ka: testing the Heinrich precursor hypothesis. *Boreas, 39,* 576-591.

Harker, A., 1901. Ice-erosion in the Cuillin Hills, Skye: *Transactions of the Royal Society of Edinburgh, 40*, 221–252.

Heyman, J., Stroeven, A.P., Harbor, J.M., and Caffee, M.W., 2011, Too young or too old: evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages: *Earth and Planetary Science Letters*, *302*, 71-80.

Hibbert FD. 2011. Dynamics of the British Ice Sheet and Prevailing Hydrographic Conditions for the Last 175,000 years: An investigation of marine sediment core MD04-2822 from the Rockall Trough. *Unpublished PhD thesis, University of St Andrews.*

Hibbert, F.D., Austin, W.E., Leng, M.J., and Gatliff, R.W., 2010, British Ice Sheet dynamics inferred from North Atlantic ice-rafted debris records spanning the last 175 000 years: *Journal of Quaternary Science*, *25*, 461-482.

Holland, D.M., Thomas, R.H., De Young, B., Ribergaard, M.H., and Lyberth, B., 2008, Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters: *Nature Geoscience*, *1*, 659-664.

Howe, J.A., Dove, D., Bradwell, T. and Gafeira, J., 2012. Submarine geomorphology and glacial history of the Sea of the Hebrides, UK. *Marine Geology*, *315*, 64-76.

Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R. and Stoker, M., 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British–Irish ice sheet. *Quaternary Science Reviews*, *28*, 758-776.

Joughin, I., Smith, B.E., and Medley, B., 2014, Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica: *Science*, *344*, 735-738.

Knutz, P.C., Austin, W.E., and Jones, E.J.W., 2001, Millennial-scale depositional cycles related to British Ice Sheet variability and North Atlantic paleocirculation since 45 kyr BP, Barra Fan, UK margin: *Paleoceanography*, *16*, 53-64.

Knutz, P.C., Zahn, R., and Hall, I.R., 2007, Centennial-scale variability of the British Ice Sheet: Implications for climate forcing and Atlantic meridionial overturning circulation during the last deglaciation: *Paleoceanography 22*.

Kristensen, L., Benn, D.I., Hormes, A. and Ottesen, D. 2009. Mud aprons in front of Svalbard surge moraines: evidence of subglacial deforming layers or proglacial tectonics? *Geomorphology* 111, 206-221.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambridge, M., 2014, Sea level and global ice volumes from the Last Glacial Maximum to the Holocene: *Proceedings of the National Academy of Science of the United States of America*, *111*, 15296-15303.

Lifton, N., Sato, T. and Dunai, T.J., 2014. Scaling in situ cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes. *Earth and Planetary Science Letters*, *386*, pp.149-160.

Livingstone, S.J., Cofaigh, C.Ó., Stokes, C.R., Hillenbrand, C.D., Vieli, A. and Jamieson, S.S., 2013. Glacial geomorphology of Marguerite Bay palaeo-ice stream, western Antarctic Peninsula. *Journal of Maps*, *9*, 558-572.

Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J. and Yu, Z.C., 2008. Synchronisation of palaeoenvironmental events in the North

Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. *Quaternary Science Reviews*, *27*, 6-17.

Marcott, S.A., Clark, P.U., Padman, L., Klinkhammer, G.P., Springer, S.R., Liu, Z., Otto-Bliesner, B.L., Carlson, A.E., Ungerer, A., Padman, J. and He, F., 2011. Ice-shelf collapse from subsurface warming as a trigger for Heinrich events. *Proceedings of the National Academy of Sciences*, *108*, 13415-13419.

Marrero, S.M., Phillips, F.M., Borchers, B., Lifton, N., Aumer, R. and Balco, G., 2016a. Cosmogenic nuclide systematics and the CRONUScalc program. *Quaternary Geochronology*, *31*, 160-187.

Marrero, S.M., Phillips, F.M., Caffee, M.W. and Gosse, J.C., 2016b. CRONUS-Earth cosmogenic ^{36}Cl calibration. *Quaternary Geochronology*, *31*, 199-219.

McCabe, A.M., and Clark, P.U., 2003, Deglacial chronology from County Donegal, Ireland: implications for deglaciation of the British–Irish ice sheet: *Journal of the Geological Society of London*, *160*, 847-855.

Murray, T., Smith, A.M., King, M.A. and Weedon, G.P., 2007. Ice flow modulated by tides at up to annual periods at Rutford Ice Stream, West Antarctica. *Geophysical Research Letters*, *34*, L18503.

Ó' Cofaigh, C., Dunlop, P. and Benetti, S., 2012. Marine geophysical evidence for Late Pleistocene ice sheet extent and recession off northwest Ireland. *Quaternary Science Reviews*, *44*, 147-159.

Ottesen, D., Dowdeswell, J.A., Benn, D.I., Kristensen, L., Christiansen, H.H., Christensen, O., Hansen, L., Lebesbye, E., Forwick, M. and Vorren, T.O., 2008. Submarine landforms characteristic of glacier surges in two Spitsbergen fjords. *Quaternary Science Reviews*, *27*, 1583-1599.

Peacock, J.D., 2008, Late Devensian palaeoenvironmental changes in the sea area adjacent to Islay, SW Scotland: implications for the deglacial history of the island: *Scottish Journal of Geology*, *44*, 183-190.

Peacock, J.D., Austin, W.E.N., Selby, I., Graham, D.K., Harland, R. and Wilkinson, I.P., 1992. Late Devensian and Flandrian palaeoenvironmental changes on the Scottish continental shelf west of the Outer Hebrides. *Journal of Quaternary Science*, *7*, 145-161.

Peck, V.L., Hall, I.R., Zahn, R., and Elderfield, H., 2008, Millennial-scale surface and subsurface paleothermometry from the northeast Atlantic, 55–8 ka BP: *Paleoceanography*, *23*, PA3221.

Peck, V.L., Hall, I.R., Zahn, R., Grousset, F., Hemming, S.R. and Scourse, J.D., 2007. The relationship of Heinrich events and their European precursors over the past 60ka BP: a multi-proxy ice-rafted debris provenance study in the North East Atlantic. Quaternary Science Reviews, 26(7), 862-875.

Ramsey, C.B., 2008. Deposition models for chronological records. *Quaternary Science Reviews*, *27*, 42-60.

Ramsey, C.B., 2013. OxCal 4.2. *Manual [online] available at: https://c14. arch. ox. ac. uk/oxcalhelp/hlp_contents. html*.

Ramsey, C.B. and Lee, S., 2013. Recent and planned developments of the program OxCal. *Radiocarbon*, *55*, 720-730.

Rasmussen, S.O., Seierstad, I.K., Andersen, K.K., Bigler,M., Dahl-Jensen, D., and Johnsen, S.J., 2008, Synchronization of the NGRIP, GRIP, and GISP2 ice cores across MIS 2 and palaeoclimatic implications: *Quaternary Science Reviews*, *27*, 18-28.

Rinterknecht, V., Jomelli, V., Brunstein, D., Favier, V., Masson-Delmotte, V., Bourlès, D., Leanni, L. and Schläppy, R., 2014. Unstable ice stream in Greenland during the Younger Dryas cold event. *Geology*, *42*, 759-762.

Robinson, M. and Ballantyne, C.K., 1979. Evidence for a glacial readvance pre-dating the Loch Lomond Advance in Wester Ross. *Scottish Journal of Geology*, *15*, 271-277.

Rosier, S.H.R., Gudmundsson, G.H. and Green, J.A.M. 2015. Temporal variations in the flow of a large Antarctic ice-stream controlled by tidally induced changes in the subglacial water system. *Cryosphere, 9,* 2397-2429.

Schimmelpfennig, I., Benedetti, L., Finkel, R., Pik, R., Blard, P H., Bourlès, D., Burnard, P., and Williams, A., 2009, Sources of in-situ ^{36}Cl in basaltic rocks. Implications for calibration of production rates: *Quaternary Geochronology*, *4,* 441-461.

Schimmelpfennig, I., Benedetti, L., Garreta, V., Pik, R., Blard, P.H., Burnard, P., Bourlès, D., Finkel, R., Ammon, K., and Dunai, T., 2011, Calibration of cosmogenic ^{36}Cl production rates from Ca and K spallation in lava flows from Mt. Etna (38° N, Italy) and Payun Matru (36° S, Argentina): *Geochimica et Cosmochimic Acta, 75*, 2611-2632.

Schimmelpfennig, I., Schaefer, J.M., Putnam, A.E., Koffman, T., Benedetti, L., Ivy-Ochs, S., ASTER team, and Schlüchter, C., 2014, ^{36}Cl production rate from K-spallation in the European Alps (Chironico landslide, Switzerland): *Journal of Quaternary Science, 29*, 407-413.

Scourse, J.D. and Furze, M.F.A., 2001. A critical review of the glaciomarine model for Irish Sea deglaciation: evidence from southern Britain, the Celtic shelf and adjacent continental slope. *Journal of Quaternary Science*, *16*, 419-434.

Scourse, J.D., Hall, I.R., McCave, I.N., Young, J.R. and Sugdon, C., 2000. The origin of Heinrich layers: evidence from H2 for European precursor events. *Earth and Planetary Science Letters*, *182*(2), pp.187-195.

Scourse, J.D., Haapaniemi, A.I., Colmenero-Hidalgo, E., Peck, V.L., Hall, I.R., Austin, W.E., Knutz, P.C. and Zahn, R., 2009. Growth, dynamics and deglaciation of the last British–Irish ice sheet: the deep-sea ice-rafted detritus record. Quaternary Science Reviews, 28(27), 3066-3084.

Scourse, J.D., Ward, S.L., Wainwright, A., Bradley, S.L. and Uehara, K. Submitted. The role of megatides and relative sea level in controlling the deglaciation of the British-Irish and Fennoscandian Ice Sheets. *Journal of Quaternary Science*.

Seierstad, I.K., Abbott, P.M., Bigler, M., Blunier, T., Bourne, A.J., Brook, E., Buchardt, S.L., Buizert, C., Clausen, H.B., Cook, E. and Dahl-Jensen, D., 2014. Consistently dated records from the Greenland GRIP, GISP2 and NGRIP ice cores for the past 104 ka reveal regional millennial-scale $\delta^{18}O$ gradients with possible Heinrich event imprint. *Quaternary Science Reviews*, *106*, pp.29-46.

Sejrup, H.P., Larsen, E., Landvik, J., King, E.L., Haflidason, H. and Nesje, A., 2000. Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region. *Quaternary Science Reviews*, *19*, 667-685.

Sissons, J.B., Lowe, J.J., Thompson, K.S. and Walker, M.J.C., 1973. Loch Lomond readvance in Grampian Highlands of Scotland: *Nature*, *244*, 75-77.

Small, D., 2012 The Deglaciation of the northwest sector of the last British-Irish Ice Sheet: Integrating onshore and offshore data relating to chronology and behaviour. *Unpublished PhD Thesis, University of St Andrews.*

Small, D., Rinterknecht, V., Austin, W., Fabel, D. and Miguens-Rodriguez, M., 2012, In situ cosmogenic exposure ages from the Isle of Skye, northwest Scotland: implications for the timing of deglaciation and readvance from 15 to 11 ka. *Journal of Quaternary Science, 27*, 150-158.

Small D., Austin W., and Rinterknecht V., 2013. Freshwater influx, hydrographic reorganization and the dispersal of ice-rafted detritus in the sub-polar North Atlantic Ocean during the last deglaciation: *Journal of Quaternary Science, 28*, 527-535.

Stoker, M. and Bradwell, T., 2005. The Minch palaeo-ice stream, NW sector of the British–Irish Ice Sheet. *Journal of the Geological Society*, *162*, 425-428.

Stoker, M.S., Wilson, C.R., Howe, J.A., Bradwell, T. and Long, D., 2010. Paraglacial slope instability in Scottish fjords: examples from Little Loch Broom, NW Scotland. *Geological Society, London, Special Publications*, *344*, 225-242.

Stokes, C.R. and Clark, C.D., 2001. Palaeo-ice streams. *Quaternary Science Reviews*, *20*, 1437-1457.

Stokes, C.R., Tarasov, L., Blomdin, R., Cronin, T.M., Fisher, T.G., Gyllencreutz, R., Hättestrand, C., Heyman, J., Hindmarsh, R.C., Hughes, A.L. and Jakobsson, M., 2015. On the reconstruction of palaeo-ice sheets: Recent advances and future challenges. *Quaternary Science Reviews*, *125*, 15-49.

Stone, J.O., 2000, Air pressure and cosmogenic isotope production: *Journal of Geophysical Research: Solid Earth, 105*, 23753-23759.

Stone, J.O., Allan, G.L., Fifield, L.K. and Cresswell, R.G., 1996. Cosmogenic chlorine-36 from calcium spallation. *Geochimica et Cosmochimica Acta*, *60*, 679-692.

Stone, J.O., Ballantyne, C.K. and Fifield, L.K., 1998. Exposure dating and validation of periglacial weathering limits, northwest Scotland. *Geology*, *26*, 587-590.

Svendsen, J.I., Briner, J.P., Mangerud, J. and Young, N.E., 2015. Early break-up of the Norwegian channel ice stream during the last glacial maximum. *Quaternary Science Reviews*, *107*, 231-242.

Uehara, K., Scourse, J.D., Horsburgh, K.J., Lambeck, K. and Purcell, A.P., 2006. Tidal evolution of the northwest European shelf seas from the Last Glacial Maximum to the present. *Journal of Geophysical Research: Oceans*, *111*, C09025.

Walker, M.J., Ballantyne, C.K., Lowe, J.J. and Sutherland, D.G., 1988. A reinterpretation of the Lateglacial environmental history of the Isle of Skye, Inner Hebrides, Scotland. *Journal of Quaternary Science*, *3*, 135-146.

Wouters, B., Martin-Español, A., Helm, V., Flament, T., van Wessem, J.M., Ligtenberg, S.R.M., van den Broeke, M.R., and Bamber, J. L., 2015, Dynamic thinning of glaciers on the Southern Antarctic Peninsula: *Science, 348*, 899-903.

Figure Captions

Figure 1. Google Earth Image with extent of the BDIS and related glaciological features. Existing geochronological dates are shown (Table 1) along with location of marine core MD04-2822. Flowlines adjusted from Bradwell et al. (2008). Dashed box shows the location of Figure 2, solid box shows location of Figure 7. Isochrones depicting the most likely ice extent at 24 ka, 17 ka, and 16 ka (shaded for clarity) are taken from Hughes et al., 2016. BDF = Barra/Donegal Fan, BDIS = Barra/Donegal Ice Stream, MIS = Minch Ice Stream. All ^{10}Be CRE dates have been re-calculated using a local production rate (Loch Lomond Production Rate) of 3.92 ± 0.18 atoms g^{-1} a^{-1} (Fabel et al., 2012).

Figure 2. Location map of Skye and northwest Scotland showing locations mentioned in text. Dashed lines demark inferred zones of confluence between mainland ice and the

Skye Ice Dome. Red stars show locations of existing exposure ages from (1) Trotternish (Stone et al., 1998) and (2) the Strollamus moraine (Small et al., 2012). GB = Glen Brittle, LS = Loch Scavaig. Arrows show generalized ice flow directions, MIS = Minch Ice Stream, BDIS = Barra-Donegal Ice Stream. Also shown are inferred limits of Wester Ross Readvance (WRR). Letters A and B denote the locations of the palaeotidal and RSL simulations (Section 5.2; Figure 11). DEM derived from NASNA SRTM 90 m data, available at http://www.sharegeo.ac.uk/handle/10672/5.

Figure 3. Map of Glen Brittle area showing sampled moraines, raised shorelines and locations of sampled boulders. The limits of the Loch Lomond Readvance and associated landforms are shown as adapted from Ballantyne (1989). Contours at 100 m intervals. See Figure 5 for location.

Figure 4. Map of the northeast corner of Soay showing sampled moraine and locations of sampled boulders. Dashed line shows crest of offshore moraine (Figure 8).

Figure 5. Site and sample photographs from Glen Brittle. (*A*) Glen Brittle looking North. Showing two parallel moraine ridges. Southern (outer) moraine with person, northern (inner) moraine with boulders on near horizon. Ice flow is towards the camera. (*B*) BRI01 boulder. (*C*) BRI-02 boulder. (*D*) BRI-03 boulder. (*E*) BRI-04 boulder.

Figure 6. Site and sample photographs from Soay. (*A*) SOAY-01 boulder. (*B*) SOAY-02 boulder. (*C*) SOAY-03 boulder. (*D*) SOAY-04 boulder. (*E*) SOAY-05 boulder. (*F*) SOAY-06 boulder. (*G*) SOAY-07 boulder. (*H*) Soay moraine onshore. The dashed white line marks the crest. The offshore continuation stretches across Loch Scavaig to the far

shore (see Figures 5 and 6). Samples were located off-shot in the wooded area to the right. Ice flow was from left to right.

Figure 7. Location of ^{36}Cl samples presented and onshore moraines in Glen Brittle and on Soay. The multibeam bathymetry of Loch Scavaig is shown alongside mapped YD ice limits modified from Ballantyne (1989). Note the distinctive offshore moraine that impinges on Soay. Failure scarp and extent of inferred slope failure (SF) is also shown. The red star in the upper right is the location of the dated Strollamus medial moraine (Benn, 1990; Small et al., 2012). NEXTmap hillshade DEM by Intermap Technologies.

Figure 8. Interpreted bathymetric map of Loch Scavaig showing the distinctive arcuate terminal moraine. Suites of recessional moraines are also highlighted. There is a distinctive glacially over-deepened basin in the western portion of the survey area. The trench in the northeastern sector is the offshore continuation of the Camasunary Fault. The red star shows the location of the vibrocore VC57/-07/844 which yielded a basal radiocarbon age of 12.8 ± 0.1 ka (Small, 2012). Also show is the failure scarp on Ben Cleat and the associated landslide deposits. NEXTmap hillshade DEM by Intermap Technologies.

Figure 9. Summary CRE age plot of ^{36}Cl samples presented here shown alongside the NGRIP oxygen isotope record ($\delta^{18}O$, ‰) (Rasmussen et al., 2008). Grey boxes show arithmetic means and uncertainties of Brittle and Soay samples respectively. The Soay samples not included in calculating moraine ages shown with hollow circles. Uncertainties are 1σ analytical uncertainties. The Younger Dryas stadial (YD) and Bølling-Allerød interstadial are also shown (B-A).

Figure 10. Proxy records of deglacial forcing for the time period of BDIS deglaciation indicated by the shaded column. (*A*) Greenland oxygen isotope records ($\delta^{18}O$, ‰) from NGRIP, GRIP and GISP2 on the GICC05 timescale (Rasmussen et al., 2008; Seierstad et al., 2014) [50 yr moving averages shown by black line] (*B*) Reconstructed ESL (Lambeck et al., 2014). Proxies relating to oceanic forcing: (*C*) Mg/Ca (*G.bulloides*) SST estimates from MD01-2461 (Porcupine Seabight, Peck et al., 2008); and MD04-2822 (Rockall Trough, Hibbert, 2011; Hibbert et al., 2010) (*D*) $\delta^{18}O$ *N.pachyderma* sinistral (‰ VPDB), (*E*) % *N.pachyderma* (sinistral), (*F*) XRF core scanning (ITRAX) TiCa (proxy for terrigeneous input) and, (*G*) total IRD flux (> 150 µm cm^{-2} ka^{-1}).

Figure 11. Relative sea level (RSL) and palaeotidal (PTM) simulations for two locations in the inner part of the BDIS adjacent to Skye. A) 57.04° N, 6.88° W and, B) 57.12° N, 6.13° W (see Figure 2 for locations). RSL simulations are based on the modified glacio-isostatic adjustment model of Lambeck and PTM simulations on a modified version of the Princeton Ocean Model forced with dynamic open ocean tide (Uehara et al., 2006). These show mean *M2* tidal ranges > 6 m throughout the deglacial phase from the Last Glacial Maximum to around 11 ka BP (spring tidal ranges would have been significantly larger). The shaded boxes in A and B show the mean exposure ages from Glen Brittle and Soay, respectively.

Table 1. Published ages referred to in the text and shown on Figure 1. Outliers are shown in italics. Clusters of CRE ages that yield acceptable x_R^2 values are shown in bold, the mean of these is shown in Figure 1. Underlined radiocarbon ages are the oldest from a site and these are used in Figure 1. CRE ages calculated using CRONUS online calculator (http://hess.ess.washington.edu; accessed April 20th 2016), Lm scaling and, Loch Lomond Production Rate of 3.92 ± 0.18 atoms g^{-1} yr^{-1} (Fabel et al. 2012). ^{14}C ages calibrated using OxCal 4.2 (Bronk-Ramsey 2013) and Marine14 (Reimer et al.,2013), ΔR=300 yr.

Reference	Location (site no. Fig. 1)	Sample name	Technique	Age (yr)	Uncert. (yr)
Clark et al. (2009)	N Donegal coast (1)	BF-04-01	CRE	17607	1772
Clark et al. (2009)	N Donegal coast (1)	BF-04-03	CRE	33035	2940
Clark et al. (2009)	N Donegal coast (1)	BF-04-04	CRE	21463	1754
Clark et al. (2009)	**N Donegal coast (1)**	**BF-04-05**	**CRE**	**20924**	**1863**
Clark et al. (2009)	**N Donegal coast (1)**	**BF-04-06**	**CRE**	**20949**	**2060**
Clark et al. (2009)	N Donegal coast (1)	BF-04-08	CRE	23251	2135
Clark et al. (2009)	**N Donegal coast (1)**	**BF-04-09**	**CRE**	**21428**	**2196**
Clark et al. (2009)	**N Donegal coast (1)**	**BF-04-10**	**CRE**	**21799**	**2190**
McCabe & Clark (2003)	N Donegal coast (2)	AA32315	^{14}C	16602	178
McCabe & Clark (2003)	N Donegal coast (2)	AA45968	^{14}C	18676	168
McCabe & Clark (2003)	N Donegal coast (2)	AA45967	^{14}C	17997	188
McCabe & Clark (2003)	N Donegal coast (2)	AA45966	^{14}C	19093	496
McCabe & Clark (2003)	N Donegal coast (2)	AA33831	^{14}C	17913	130
<u>McCabe & Clark (2003)</u>	<u>N Donegal coast (2)</u>	<u>AA33832</u>	<u>^{14}C</u>	<u>20308</u>	<u>148</u>
Peacock (2008)	Islay (3)	SUERC-13122	^{14}C	14457	163
Peacock (2008)	Islay (3)	SUERC-13123	^{14}C	14337	149
<u>Peacock (2008)</u>	<u>Islay (3)</u>	<u>SUERC-13124</u>	<u>^{14}C</u>	<u>14498</u>	<u>166</u>
Ballantyne et al. (2014)	Jura (4)	SNC-02	CRE	14006	1690
Ballantyne et al. (2014)	Jura (4)	SNC-03	CRE	12352	1414
Ballantyne et al. (2014)	**Jura (4)**	**SNC-06**	**CRE**	**16875**	**1102**
Ballantyne et al. (2014)	**Jura (4)**	**SNC-07**	**CRE**	**16819**	**1025**
Baltzer et al. (2010)	W coast of Scotland (5)	UL2853	^{14}C	16587	311
Small et al., (2013)	Mid Shelf (5)	AAR-2606	^{14}C	16664	279

Table 2. Sample information for all ^{36}Cl samples from Glen Brittle and Soay.

Sample Name	Lat.	Long.	Elevation (m)	Shielding correction	Sample thickness (cm)	Lithology	Density (g/cm)
Glen Brittle							
BRI01	57.21595	-6.29651	10	0.9891	2.3	Basalt	2.6
BRI02	57.21652	-6.29641	11	0.9891	3.2	Basalt	2.6
BRI03	57.21667	-6.29678	10	0.9891	1.5	Basalt	2.6
BRI04	57.21602	-6.29554	11	0.9891	2.2	Basalt	2.6
Isle of Soay							
SOAY01	57.16073	-6.18362	13	0.9993	2.5	Gabbro	2.6
SOAY02	57.16079	-6.18352	14	0.9993	1.4	Gabbro	2.6
SOAY03	57.16118	-6.18385	15	0.9993	1.5	Gabbro	2.6
SOAY04	57.16125	-6.18392	15	0.9993	1.7	Gabbro	2.6
SOAY05	57.16120	-6.18389	9	0.9993	1.5	Gabbro	2.6
SOAY06	57.16067	-6.18340	10	0.9993	1.4	Gabbro	2.6
SOAY07	57.16076	-6.18362	15	0.9993	1.6	Gabbro	2.6

Table 3. Chemical and analytical data for all ^{36}Cl samples. Ratios are rounded to two significant figures. Calculated concentrations reflect precision of AMS measurements.

Sample Name	Sample mass (g)	Carrier added (g)	^{35}Cl/^{37}Cl	Uncert. (%)	^{36}Cl/^{35}Cl	Uncert. (%)	^{36}Cl/^{37}Cl	Uncert. (%)	^{36}Cl conc. (at g^{-1})	Uncert. (abs)
Glen Brittle										
BRI01	15.1294	0.4844	9.55E+01	0.931	5.73E-14	6.576	5.46E-12	6.548	110167	7943
BRI02	14.9876	0.4824	1.08E+02	1.216	3.81E-14	6.223	4.11E-12	6.180	70422	5140
BRI03	15.0566	0.4818	1.05E+02	0.646	5.87E-14	5.557	6.16E-12	5.509	112557	6893
BRI04	12.9649	0.4824	1.30E+02	0.692	4.55E-14	8.045	5.91E-12	8.012	98678	8902
Soay										
SOAY01	20.0777	0.4853	5.59E+01	0.571	6.92E-14	4.806	3.86E-12	4.751	98972	5545
SOAY02	20.0711	0.4853	1.73E+01	0.253	6.81E-14	5.188	1.18E-12	5.135	113848	6786
SOAY03	20.0162	0.4787	2.40E+01	0.345	5.70E-14	5.297	1.37E-12	5.247	86176	5447
SOAY04	20.0341	0.478	2.26E+01	0.535	3.79E-14	6.449	8.56E-13	6.408	53701	4515
SOAY05	16.8693	0.4781	2.33E+01	0.883	5.68E-14	5.147	1.32E-12	5.096	108742	6183
SOAY06	20.1048	0.4816	6.39E+00	0.276	6.34E-14	5.954	4.04E-13	5.909	179705	12009
SOAY07	19.9611	0.4818	7.73E+00	0.379	6.19E-14	5.31	4.78E-13	5.262	150704	8986

Table 4. Whole rock geochemistry of samples from Glen Brittle and Soay.

Sample Name	SiO_2 (wt-%)	Na_2O (wt-%)	MgO (wt-%)	Al_2O_3 (wt-%)	MnO (wt-%)	H_2O (wt-%)	Sm (ppm)	Gd (ppm)	K_2O (wt -%)	CaO (wt-%)	Cl (ppm)	TiO_2 (wt-%)	Fe_2O_3 (wt-%)	P_2O_5 (wt -%)	U (ppm)	Th (ppm)
Glen Brittle																
BRI01	46.19	1.96	8.62	13.17	0.17	2.42	2.61	3.25	0.301	12.16	2.76	1.85	13.06	0.01	0.04	0.16
BRI02	41.99	1.60	13.1	12.04	0.2	2.18	3.9	4.39	0.18	7.90	2.13	2.78	17.85	0.06	0.08	0.32
BRI03	47.64	1.99	8.52	13.68	0.16	2.01	7.26	3.09	0.18	11.97	2.25	1.77	11.98	0.02	0.04	0.15
BRI04	46.71	1.75	8.92	12.05	0.18	1.83	2.66	3.3	0.26	13.08	1.53	2.10	13.01	0.02	0.04	0.12
Soay																
SOAY01	45.77	0.96	11.07	20.13	0.09	0.44	0.5	0.82	0.03	14.08	4.69	0.27	7.11	0.02	0.02	0.11
SOAY02	44.55	1.03	12.49	20.96	0.09	0.41	1.30	0.69	< 0.005	12.99	23.69	0.25	7.17	0.02	< 0.01	0.03
SOAY03	44.92	1.01	13.01	22.26	0.06	0.48	0.15	0.33	< 0.005	13.16	15.14	0.1	4.97	0.01	< 0.01	0.02
SOAY04	42.94	0.07	28.02	10.14	0.13	0.62	0.28	0.5	<0.005	7.28	16.32	0.18	10.34	0.01	0.01	0.06
SOAY05	47.12	1.58	1.88	29.28	0.04	0.56	0.56	0.87	0.02	16.46	19.06	0.34	2.74	0.02	0.02	0.10
SOAY06	47.08	1.25	5.76	23.44	0.09	1.30	0.40	0.71	0.06	15.87	109.82	0.19	4.90	0.02	< 0.01	0.01
SOAY07	48.15	0.51	12.79	8.85	0.18	1.36	1.57	2.66	0.04	15.74	77.84	0.63	11.63	0.02	< 0.01	0.02

Table 5. Comparison of CRE ages from Skye calculated using alternative calculation methods and scaling schemes. Full uncertainties (analytical uncertainties). CRE ages used in interpretation highlighted in bold text.

Calc. method	*Schimmelpfenig et al. (2009)*		*Marrerro et al. (2016a)*		Marrerro et al. (2016a)	
Prod. rates	*Marrero et al. (2016b)*		*Marrero et al. (2016b)*		Marrero et al. (2016b)	
Scaling	*Lm*		*Lm*		*SA*	
	Age	*Uncert.*	*Age*	*Uncert.*	Age	Uncert.
SOAY1	*17.2*	*2.1 (1.5)*	*17.0*	*1.8 (1.5)*	**15.0**	**1.3 (0.9)**
SOAY2	*19.0*	*2.3 (1.5)*	*19.0*	*2.0 (1.5)*	**16.4**	**1.5 (1.0)**
SOAY3	*14.9*	*1.8 (1.4)*	*14.6*	*1.6 (1.4)*	12.9	1.2 (0.8)
SOAY4	*15.0*	*1.9 (1.6)*	*14.7*	*1.8 (1.6)*	13.0	1.4 (1.1)
SOAY5	*15.2*	*1.8 (1.0)*	*14.9*	*1.5 (1.0)*	13.1	1.1 (0.8)
SOAY6	*17.6*	*2.5 (1.1)*	*16.9*	*2.4 (1.1)*	**14.8**	**1.8 (1.0)**
SOAY7	*17.2*	*2.2 (0.9)*	*17.0*	*2.0 (0.9)*	**14.6**	**1.5 (0.9)**
BRI01	*19.0*	*2.4 (1.4)*	*20.6*	*2.2 (1.5)*	**18.2**	**1.7 (1.3)**
BRI02	*18.9*	*2.2 (1.4)*	*19.4*	*2.1 (1.5)*	**17.3**	**1.6 (1.3)**
BRI03	*21.9*	*2.6(1.4)*	*22.0*	*2.3 (1.4)*	**19.4**	**1.7 (1.2)**
BRI04	*17.3*	*2.1 (1.6)*	*17.5*	*2.1 (1.6)*	**15.5**	**1.7 (1.4)**