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Cosmogenic exposure age constraints on deglaciation and flow behaviour of a marine-based ice stream in western Scotland, 21–16 ka

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A B S T R A C T

Understanding how marine-based ice streams operated during episodes of deglaciation requires geochronological data that constrain both timing of deglaciation and changes in their flow behaviour, such as that from unconstrained ice streaming to topographically restricted flow. We present seventeen new ^{10}Be exposure ages from glacial boulders and bedrock at sites in western Scotland within the area drained by the Hebrides Ice Stream, a marine-based ice stream that drained a large proportion of the former British-Irish Ice Sheet. Exposure ages from Tiree constrain deglaciation of a topographic high within the central zone of the ice stream, from which convergent flowsets were produced during ice streaming. These ages thus constrain thinning of the Hebrides Ice Stream, which, on the basis of supporting information, we infer to represent cessation of ice streaming at 20.6 $\pm$ 1.2 ka, 3–4 ka earlier than previously inferred. A period of more topographically restricted flow produced flow indicators superimposed on those relating to full ice stream conditions, and exposure ages from up-stream of these constrain deglaciation to 17.5 $\pm$ 1.0 ka. Complete deglaciation of the marine sector of the Hebrides Ice Stream occurred by 17–16 ka at which time the ice margin was located near the present coastline. Exposure ages from the southernmost Outer Hebrides (Mingulay and Barra) indicate deglaciation at 18.9 $\pm$ 1.0 and 17.1 $\pm$ 1.0 ka respectively, demonstrating that an independent ice cap persisted on the southern Outer Hebrides for 3–4 ka after initial ice stream deglaciation. This suggests that deglaciation of the Hebrides Ice Stream was focused along major submarine troughs. Collectively, our data constrain initial deglaciation and changes in flow regime of the Hebrides Ice Stream, final deglaciation of its marine sector, and deglaciation of the southern portion of the independent Outer Hebrides Ice Cap, providing chronological constraints on future numerical reconstructions of this key sector of the former British-Irish Ice Sheet.

1. Introduction

Ice streams are faster flowing corridors of ice that exert a major control on the mass balance of ice sheets both past and present (Stokes and Clark, 2001; Bennett, 2003; Stokes et al., 2016). They extend into the accumulation zones of ice sheets and, as well as draining large areas, act as conduits to transmit the effects of external perturbations, such as changes in ocean temperature, air temperature or sea-ice distribution, from periphery to interior (Payne et al., 2004; Shepherd et al., 2004; Stokes et al., 2005; Roberts et al., 2010; Favier et al., 2014). Temporal constraints on ice stream evolution therefore provide information on the dynamics of former ice sheets and are vital for empirical reconstructions of past ice sheet deglaciation (e.g. Hughes et al., 2016). In turn these provide data to test the numerical ice sheet models that are fundamental to predicting future sea-level rise

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from modern day ice sheet decay in Greenland and Antarctica (e.g. Alley et al., 2005; DeConto and Pollard, 2016).

Studies of extant ice sheets have observed a range of behaviour in ice streams including acceleration, deceleration, stagnation, reactivation, and migration (Retzlaff and Bentley, 1993; Jacobel et al., 1996; Anandakrishnan et al., 2001; Conway et al., 2002; Hulbe and Fahnestock, 2004; Joughin et al., 2004; Catania et al., 2006; Howat et al., 2007). However, given the temporal limitations of modern observations, understanding the longer-term significance of such changes remains challenging. In this context palaeo-ice streams provide a geomorphological record of ice stream evolution from maximum extent to final deglaciation and can be used to place observed changes in context (e.g. Stokes et al., 2009; Winsborrow et al., 2012; Hughes et al., 2014; Stokes et al., 2016). Reconstructions of past ice streams were initially hindered by the scale of the geomorphological evidence they leave behind with suites of landforms delimiting their extent and flow directions extending over large areas (~10^3–10^5 km^2) that are often relatively

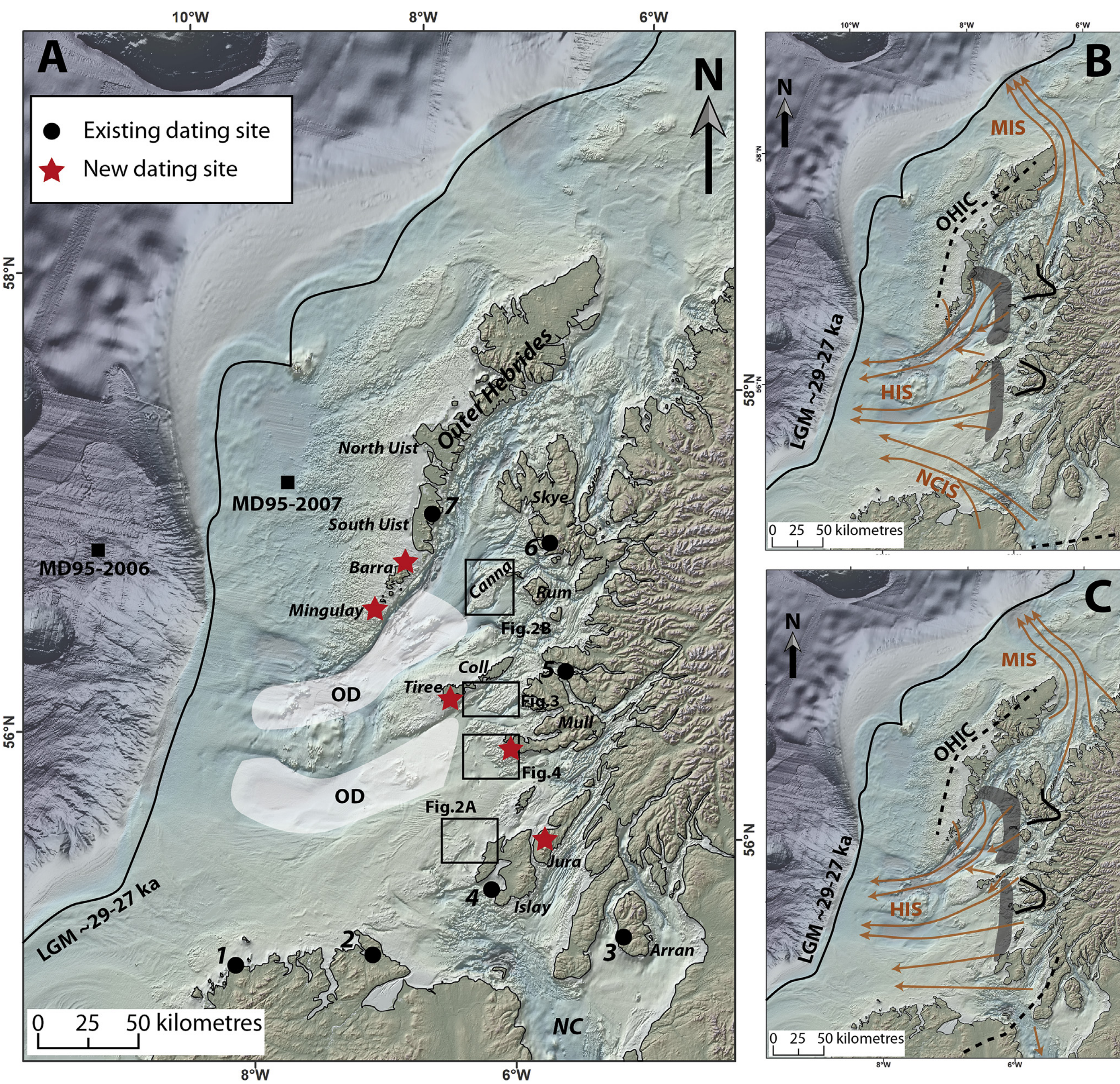

Fig. 1. A. Location map of the Hebrides with regional bathymetry showing the place names mentioned in the text. Black dots indicate existing geochronological data, numbered as in Table 1 (for clarity the existing data from Jura are not numbered). Red stars indicate sites included in this study. White shaded areas are glacial overdeepenings (OD = overdeepening) formerly occupied by the Hebrides Ice Stream. Maximum extent of BIIS as depicted by Bradwell et al. (2008) and adapted by Hiemstra et al. (2013). NC = North Channel. B and C. postulated flowlines of the Hebrides Ice Stream.: (B) during the earlier stage of ice streaming when it was influenced by ice flowing from the North Channel (Finlayson et al., 2014; Hughes et al., 2014); (C) during the later stage of ice streaming when the Hebrides Ice Stream was not influenced by North Channel ice (Dove et al., 2015). The major ice divides relevant to the Hebrides Ice Stream are shown (black dashed lines), including independent ice domes over Skye and Mull (solid black lines). Inferred onset zones of the HIS are shown with black shading in panels B and C. The flowlines of the neighbouring Minch Ice Stream [MIS] (Bradwell et al., 2008) are also shown. HIS = Hebrides Ice Stream, OHIC = Outer Hebrides Ice Cap, NCIS = North Channel Ice Stream. Boxes denote extent of Figs. 2–4. Location of marine cores mentioned in the text are also shown. Bathymetry from EMODNET, onshore hillshaded DEM from Intermap Technologies NEXTMap Britain elevation data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)