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Cosmogenic ^{36}Cl exposure ages reveal a 9.3 ka BP glacier advance and the Late Weichselian-Early Holocene glacial history of the Drangajökull region, northwest Iceland

Skafti Brynjólfsson [a, b, c, *], Anders Schomacker [a, d], Ólafur Ingólfsson [b, e], Jakob K. Keiding [f]

[a] Department of Geology, Norwegian University of Science and Technology, Sem Sælands veg 1, N-7491 Trondheim, Norway
[b] Institute of Earth Sciences, University of Iceland, Askja, Sturlugata 7, IS-101 Reykjavík, Iceland
[c] Icelandic Institute of Natural History, Borgum við Norðurslóð, IS-602 Akureyri, Iceland
[d] Centre for GeoGenetics, Natural History Museum of Denmark, University of Copenhagen, Øster Voldgade 5-7, DK-1350 Copenhagen K., Denmark
[e] The University Centre in Svalbard (UNIS), Box 156, N-9171 Longyearbyen, Norway
[f] Geological Survey of Norway, P.O. Box 6315 Sluppen, N-7491 Trondheim, Norway

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ABSTRACT

We present twenty-four new cosmogenic isotope (^{36}Cl) surface exposure ages from erratic boulders, moraine boulders and glacially eroded bedrock that constrain the late Weichselian to Holocene glacial history of the Drangajökull region, northwest Iceland. The results suggest a topographically controlled ice sheet over the Vestfirðir (Westfjords) peninsula during the last glaciation. Cold based non-erosive sectors of the ice sheet covered most of the mountains while fjords and valleys were occupied with erosive, warm-based ice.

Old ^{36}Cl exposure ages from highlands and mountain plateaux (L8; 76.5 ka and H1; 41.6 ka) in combination with younger erratic boulders (L7; 26.2 and K1–K4; 15.0–13.8 ka) superimposed on such surfaces suggest the presence of non-erosive ice over uplands and plateaux in the Vestfirðir peninsula during the last glaciation. Glacially scoured terrain and erratic boulders yielding younger exposure ages (L1-L6; 11.3–9.1 ka and R1, R6-R7; 10.6–9.4 ka) in the lowland areas indicate that the valleys and fjords of the Vestfirðir peninsula were occupied by warm-based, dynamic ice during the last glaciation.

The deglaciation of mountain Leirufjall by 26.2 ka BP suggests that ice thinning and deglaciation of some mountains and plateaux preceded any significant lateral retreat of the ice sheet. Subsequently this initial ice thinning was followed by break-up of the shelf based ice sheet off Vestfirðir about 15 ka BP. Hence, the new exposure ages suggest a stepwise asynchronous deglaciation on land, following the shelf break-up with some valleys and most of the highlands, ice free by 14–15 ka BP.

The outermost moraine at the mouth of Leirufjörður is dated to 9.3 ka BP, and we suggest the moraine to be formed by a glacier re-advance in response to a cooler climate forced by the reduced Atlantic Meridional Overturning Circulation at around 9.3 ka BP. A system of moraines proximal to the 9.3 ka moraine in Leirufjörður as well as a 9.4 ka deglaciation age in the coastal area of Reykjarfjörður suggest that an extensive ice cap persisted over the eastern Vestfirðir peninsula at least until c. 9 ka BP.

1. Introduction

Identifying temporal and spatial changes of the last Icelandic ice sheet (IIS) is essential to improve our understanding of its interactions with ocean-atmospheric systems in the North Atlantic during the late Pleistocene and early Holocene (Ingólfsson, 1991; Eiríksson et al., 2000; Hubbard et al., 2008; Norðdahl et al., 2008; Geirsdóttir et al., 2009; Ingólfsson et al., 2010). Iceland is located at the boundary between the relative warm Atlantic water of the

Abbreviations: IIS, Icelandic Ice Sheet; AMOC, Atlantic Meridional Overturning Circulation; LGM, Last Glacial Maximum; LIA, Little Ice Age; AMS, Accelerator Mass Spectrometry.

* Corresponding author. Department of Geology, Norwegian University of Science and Technology, Sem Sælands veg 1, N-7491 Trondheim, Norway.
E-mail address: skafti.brynjolfsson@ntnu.no (S. Brynjólfsson).

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Irminger Current and the relatively cold polar water of the East Greenland Current, thus making Icelandic glaciers highly sensitive to changes in oceanic and atmospheric circulation (Bergþórsson, 1969; Eiríksson et al., 2000; Flowers et al., 2007, 2008; Geirsdóttir et al., 2009). The Atlantic Meridional Overturning Circulation (AMOC) supplies the high latitudes of the Atlantic with warm ocean surface water which makes for relatively mild climate there. However, large pulses of freshwater into the North Atlantic which reduce or temporarily shut down the northward heat transport by the AMOC cause climatic deteriorations (Alley and Ágústsdóttir, 2005; Lewis et al., 2012). Climatic cooling events ca. 9.2–9.3 ka and 8.2 ka BP, probably caused by meltwater pulses from Lake Agassiz to the Atlantic Ocean, can be identified in various paleo-archives (Alley et al., 1997; Clarke et al., 2004; Kaufman et al., 2004; Teller et al., 2005; Fleitman et al., 2008; Kleiven et al., 2008; Murton et al., 2010; Yu et al., 2010; Solomina et al., 2015). Proxies for climatic deterioration during these periods in Iceland have been identified in marine and lacustrine sediment cores (Eiríksson et al., 2000; Geirsdóttir et al., 2009; Larsen et al., 2012), but glacier responses to those events have hitherto not been recognized in Iceland.

Our understanding of the Late Weichselian and Holocene environmental history of Iceland has developed significantly during the last two to three decades. Conceivably the most important advancement has been a new concept recognizing that the IIS was a very dynamic and rapidly changing ice sheet, compared to a concept of a gradually changing ice sheet in earlier reconstructions (Norðdahl et al., 2008; Ingólfsson et al., 2010). Reconstructions of configuration, dynamics, and thermal conditions of the IIS during the Last Glacial Maximum (LGM) and deglaciation still suffer from a lack of high-resolution chronological data, especially the direct dating of terrestrial landforms and sediments (Andresen et al., 2005; Caseldine et al., 2006; Hubbard et al., 2008; Norðdahl et al., 2008 Geirsdóttir et al., 2009, 2013).

Two main concepts have been proposed for the LGM in northwest Iceland; an independent, restricted ice cap that partly occupied the Vestfirðir peninsula without merging with the main IIS, i.e. leaving nunataks, coastal areas and mountains ice free in between ice-streams which drained through fjords and valleys (Thoroddsen, 1911; Þórarinsson, 1937; Sigurvinsson, 1983; Hjort et al., 1985; Ingólfsson, 1991; Norðdahl, 1991; Rundgren and Ingólfsson, 1999; Andrews et al., 2002; Principato et al., 2006). More recently it was suggested that the Vestfirðir ice cap and the main IIS coalesced into one large ice sheet covering most of the country, except some coastal mountains, and extending out towards the shelf break (Syvitski et al., 1999; Norðdahl and Pétursson, 2005; Hubbard et al., 2008; Norðdahl et al., 2008; Geirsdóttir et al., 2009). Lack of directly dated glacial landforms and sediments makes it difficult to configurate of the last glaciation over Vestfirðir peninsula, and it remains to firmly establish whether ice free refugia existed during the Weichselian (Rundgren and Ingólfsson, 1999; Norðdahl et al., 2008; Ingólfsson et al., 2010).

At the LGM the Vestfirðir ice sheet is considered to have reached 10–30 km out on the shelf to the northwest of Ísafjarðardjúp and 6 km to the north of Hornstrandir (Fig. 1; Hjort et al., 1985; Andrews et al., 2002; Geirsdóttir et al., 2002). The IIS retreated rapidly from the shelf ca. 15 ka BP, probably controlled by rapidly rising eustatic sea level (Syvitski et al., 1999; Andrews et al., 2000, 2002; Eiríksson et al., 2000; Ingólfsson and Norðdahl, 2001; Geirsdóttir et al., 2002; Norðdahl and Pétursson, 2005). The absence of ice rafted debris (IRD) in sediment cores by 15 ka BP has been interpreted to suggest a rapid deglaciation of the Vestfirðir shelf, but IRD peaks between 12 and 10 ka BP indicate calving-glaciers in the Jökulfirðir fjord system, and finally absence of IRD by 10.2 ka BP suggests ice retreat on shore and just minor ice caps over the highlands (Fig. 1; Andrews et al., 2002; Gerisdóttir et al., 2002, 2009; Castañeda et al., 2004). Furthermore, the presence of the Saksunarvatn tephra in a few terrestrial localities around Drangajökull confirms that northeastern Vestfirðir peninsula was at least partly ice free by 10.2 ka BP (Hjort et al., 1985; Principato et al., 2006; Hole, 2015).

Cosmogenic exposure dating is widely applied to glacial landforms where the chronological control of glacier fluctuations can otherwise be restricted (Gosse and Phillips, 2001; Briner et al., 2005; Dunai, 2010; Balco, 2011; Young et al., 2011, 2013). Principato et al. (2003, 2006) demonstrated the potential of ^{36}Cl exposure dating to obtain absolute ages of glacial landforms in northeastern Vestfirðir. Their exposure ages indicate some ice free coastal mountains ca. 20 ka BP, and the deglaciation of valleys about 11.7 ka and 14.6 ka BP (Principato, 2003; Principato et al., 2006). However, the age calculations suffered from uncertainty in the ^{36}Cl production rates (Principato et al., 2006).

Here, we present twenty-four ^{36}Cl exposure ages of rock samples from erratic boulders, moraine boulders, and glacially sculpted bedrock. They are used along with the exposure ages from Principato et al. (2006) to reconstruct the glacial history of the Vestfirðir area. Additionally, we investigated six river-cut sediment profiles in the Reykjarfjörður valley.

The aim of this study is to reconstruct the Late Weichselian to Holocene glacial history, obtain chronological control of the last deglaciation as well as constrain the terrestrial glacial conditions of the Drangajökull ice cap and northeast Vestfirðir peninsula from LGM until the early Holocene.

2. Setting

The Vestfirðir peninsula (Fig. 1), located approximately at 66°N and 23°W, consists mainly of Miocene sub-aerial tholeiitic and porphyritic basalts, interbedded with thin sediment layers, and some outcrops of olivine basalts and volcanoclastic sedimentary horizons. Several outcrops of rhyolites indicate the presence of a few Tertiary central volcanoes buried in the lava pile of Vestfirðir which might affect local erosion rate of the bedrock (Sæmundsson, 1979; Einarsson, 1991; Kristjánsson and Jóhannesson, 1994; Guðmundsson et al., 1996; Harðarson et al., 1997). The landscape is characterized by steep-sided glacially shaped fjords and valleys, frequently confined by 500–700 m high basaltic plateaux. However, the northeastern part of Vestfirðir constitutes a relatively large, 350–600 m a.s.l. highland hosting the Drangajökull ice cap (Fig. 1a). Surfaces of the basaltic plateaux outside Drangajökull are commonly characterized by block fields, with 2–4 m wide surface polygons or sorted stripes. Glacial sediments are mostly absent in the block fields, except for scattered, relatively fresh-looking erratic boulders. Erratic boulders are numerous at lowland locations, but only rarely occur on the highlands and plateaux on the northeastern Vestfirðir peninsula (Brynjólfsson et al., 2014). However, a diamict cover of either locally weathered bedrock or till occurs sporadically on the uplands.

The Hornstrandir area, roughly 25 km north of the Drangajökull ice cap, constitutes an alpine landscape with numerous valley glaciers and cirques (Fig. 1), This topography might suggest that mountain plateaux and coastal capes could have been ice free during the last glaciation (Sugden and John, 1976; Símonarson, 1979; Hjort et al., 1985; Principato et al., 2006).

The dome shaped Drangajökull ice cap, situated 100–915 m a.s.l., has a relatively low mean equilibrium line altitude (ELA), at about 550–600 m a.s.l., compared to 1000–1300 m a.s.l. on other ice caps in Iceland (Eythorsson, 1935; Björnsson, 1979; Björnsson and Pálsson, 2008). Drangajökull extended over 190–215 km^2 during the LIA maximum (Sigurðsson et al., 2013; Brynjólfsson et al., 2014, 2015) and now covers about 142 km^2 (Jóhannesson