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Age of the Ørkendalen moraines, Kangerlussuaq, Greenland: constraints on the extent of the southwestern margin of the Greenland Ice Sheet during the Holocene

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ABSTRACT

Although Greenland ice core records register relatively stable Holocene climate conditions, the lower elevation margins of the Greenland Ice Sheet (GrIS) experienced significant Holocene fluctuations. These fluctuations include ice sheet recession during the Holocene Thermal Maximum (9–5 ka) and advance during the Little Ice Age (LIA; ~A.D. 1350–1880). Determining the extent and timing of these fluctuations is important for understanding the response of the GrIS to interglacial climate conditions both warmer and colder than at present and for developing accurate ice sheet models. Sets of moraines marking past extents of the southwestern GrIS margin occur in the Kangerlussuaq region. We focus on the Ørkendalen moraines, a prominent moraine set located within 2 km of the modern ice margin and just outboard of the LIA moraines. We present the first ^{10}Be ages of the Ørkendalen moraines indicating they were deposited at 6.8 ± 0.3 ka. The geomorphic relationship between the Ørkendalen and LIA moraines indicates that the ice sheet margin was inboard of its Ørkendalen extent between ~6.8 ka and the culmination of the LIA. The age of the Ørkendalen moraines provides an important constraint on the extent of the southwestern GrIS during the middle Holocene.

1. Introduction

Although Holocene temperature variations registered by Greenland ice cores are small in comparison to those of the last glacial period, the climatically sensitive Greenland Ice Sheet (GrIS) margins experienced significant Holocene fluctuations (Cuffey and Clow, 1997; Stuiver and Grootes, 2000; Simpson et al., 2009; Vinther et al., 2009). For example, while boreholes near the GrIS summit register temperatures only ~2.5 °C warmer than present during the Holocene Thermal Maximum (HTM, ~9–5 ka; Dahl-Jensen et al., 1998; Kaufman et al., 2004), the southwestern ice sheet margin receded as much as 80 km inboard of its present-day limit (Simpson et al., 2009). Whereas GrIS boreholes register a ~1 °C cooling during the Little Ice Age (LIA; ~1350–1880 A.D.; Dahl-Jensen et al., 1998; Grove, 2001) the ice sheet margin advanced to its maximum Holocene extent during this time (e.g. Weidick, 1984; Hall et al., 2008; Kelly et al., 2008). Establishing constraints on the Holocene GrIS margins provides insight into the response of the ice sheet to interglacial climate conditions and informs the development and calibration of ice sheet models (e.g. van Tatenhove et al., 1996a; Huybrechts, 2002; Simpson et al., 2009; Briner et al., 2010; Young et al., 2011).

An excellent geomorphic record of the extent of the GrIS during the Holocene exists in southwestern Greenland near Kangerlussuaq (Fig. 1; Supplementary material). Sets of moraines mark periods of readvance or stability between the continental shelf and the present-day ice margin (Ten Brink, 1975). The oldest moraine set, known as the Hellefisk moraines, is located on the continental shelf ~100 km offshore from Sisimiut (Fig. 1) and is assumed to have been deposited during or just subsequent to the Last Glacial Maximum (Kelly, 1985) (LGM, 26.5–20 ka, Clark et al., 2009). There are no absolute ages from this moraine set. Subsequent to the LGM, the GrIS receded onshore by ~10.8 cal kyr BP, based on a minimum-limiting radiocarbon age ~5 km north of Sisimiut (Bennike et al., 2011). Moraine sets trending approximately north-south reflect the overall eastward retreat of the GrIS through the early to middle Holocene (Fig. 1). The youngest moraine set, located <100 m from the present ice margin, is unweathered and hosts little-to-no vegetation or soil development. Based on historical records, the GrIS was depositing at least part of this moraine in 1880 A.D., at the culmination of the LIA (Weidick, 1968). This region preserves terrestrial evidence of the GrIS extents

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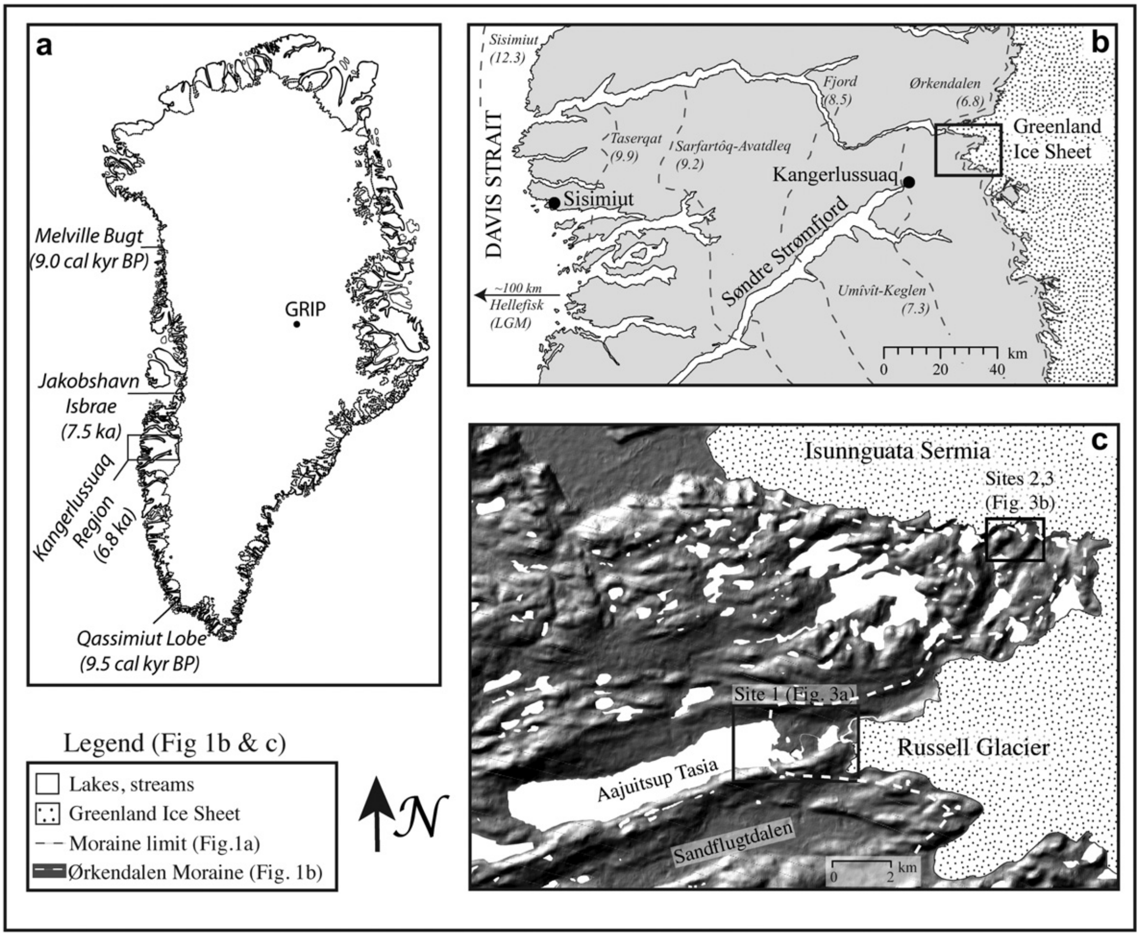

Fig. 1. a) Location of study area of Kangerlussuaq region (open rectangle) and other locations discussed in the text. Ages of deglaciation on landscape distal to the late Holocene ice sheet extent in parentheses below each location. b) Kangerlussuaq region with names, ages (in cal kyr BP) and locations of mapped moraines (grey dashed lines) referred to in text (after Ten Brink, 1975; Weidick, 1976; van Tatenhove et al., 1996b). Note that the ages of these moraines have high uncertainty (e.g. Weidick, 1972; Kelly, 1985). The LIA moraines are within 100 m of the modern ice margin and therefore the modern ice margin can be used to approximate the LIA moraines on this scale. Study location outlined by black rectangle. c) Geomorphic map showing locations of sites relative to the Ørkendalen moraines. The type locality of the Ørkendalen moraines, the Ørkendalen, is ~7 km south of the Sandflugtdalen.

during middle Holocene time, which is rare due to the extensive late Holocene advance that covered early to middle Holocene deposits in many locations.

Here we focus on the Ørkendalen moraines, originally termed the *Ørkendalen moraine system* by Ten Brink (1975), after their type locality in the eastern end of the Ørkendalen (Desert Valley), ~7 km south of the Sandflugtdalen (Fig. 1c). The Ørkendalen moraines, as mapped by Ten Brink (1975) extend ~20 km north of and ~90 km south of the Ørkendalen. They are located <2 km outboard of the present-day ice sheet margin and the LIA moraines. The Ørkendalen moraines likely represent a period of readvance or stabilization during the overall deglaciation from the last ice age. In places, the Ørkendalen moraines are partially overlain or cross cut by the LIA moraines (Fig. 2).

Previous studies have used maximum- and minimum-limiting radiocarbon ages to constrain the age of the Ørkendalen moraines (Table S1; Supplementary material). We review these ages here and report them in thousands of calibrated years before present (cal kyr BP). Ten Brink (1975) estimated the Ørkendalen moraine age at 0.3–0.7 cal kyr BP based on basal organics in an Ørkendalen moraine-dammed lake and lichenometry on moraine boulders (Fig. 3). This age was revised by van Tatenhove et al. (1996b) to 6.8 ± 0.3 cal kyr BP using basal organic matter in lake sediments and buried peat deposits both outboard and inboard of the Ørkendalen moraines. We present the

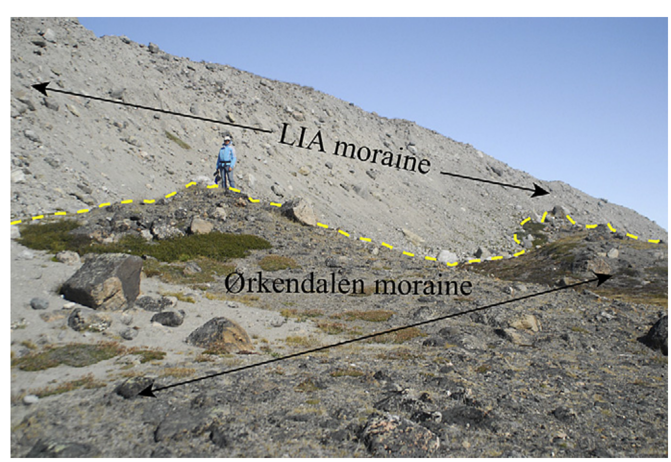

Fig. 2. View, to the northeast, of the Ørkendalen moraines highlighting the stratigraphic relationship of the Ørkendalen and LIA moraines. Location marked on Fig. 3. The yellow dashed line marks the contact between the LIA moraine (background) and the Ørkendalen moraine (foreground). The Ørkendalen moraines (foreground) are 1–2 m high with sloping crests with vegetation consisting of *Salix glauca*, *Betula nana*, *Vaccinium uliginosum* and various graminoids. The LIA moraines are 6–8 m high with sharp crests and less than 5% vegetation cover.

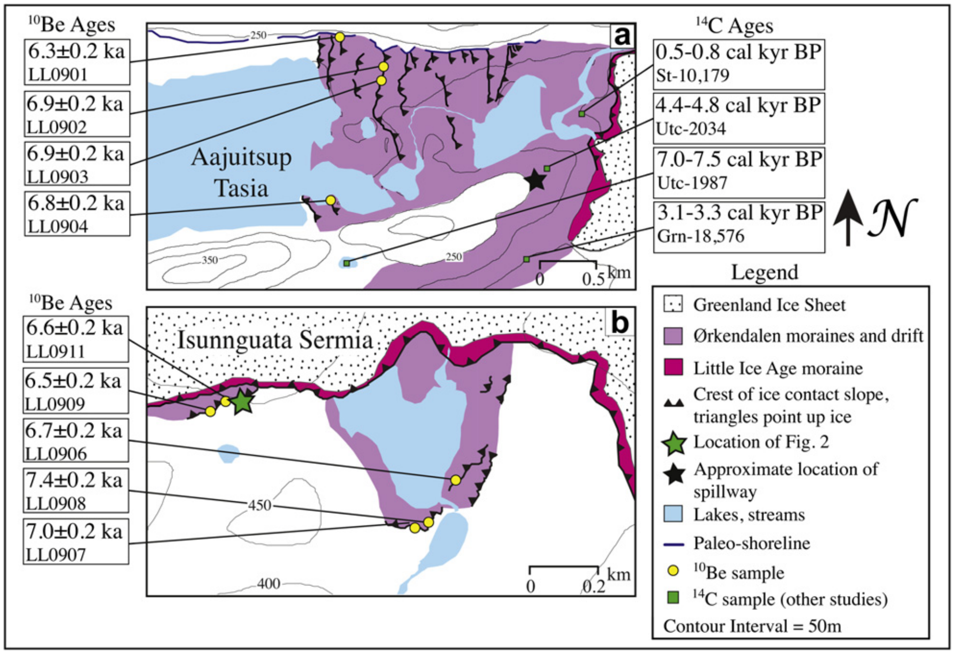

Fig. 3. Geomorphic maps of study areas. Moraines were mapped using 0.5 m Global World View satellite imagery and then checked in the field. Locations of sampled boulders were marked using a handheld Garmin GPS (model 76CSx). a) Site 1 in Moraine Valley. ^{10}Be ages from Ørkendalen moraines (this study, yellow dots) and ^{14}C samples previously used by van Tatenhove et al. (1996b) to constrain the age of the Ørkendalen moraines (this study, green squares); b) Geomorphic map of Sites 2 and 3 along the southern margin of Isunnguata Sermia with ^{10}Be ages on Ørkendalen moraines (this study, yellow dots). Contour interval is 50 m.

first surface exposure (^{10}Be) ages of the Ørkendalen moraines, complementing the existing radiocarbon chronology and providing an independent test of the age of the moraines. Determining a precise age of the Ørkendalen moraines provides an important constraint on the GrIS extent during the middle Holocene, a time when only sparse data exists on the limit of the GrIS.

2. Methods

We applied ^{10}Be dating to determine Ørkendalen moraine ages. We obtained samples from boulders atop moraines in three locations: site 1) Moraine Valley; site 2) southeast of Isunnguata Sermia; and site 3) the southern margin of Isunnguata Sermia (Figs. 1–3). We sampled upper surfaces of large boulders (>1 m in height) in stable positions on moraine crests using the drill-and-blast method of Kelly (2003). To estimate the amount of surface erosion we compared the sampled surface height to glacial polished surfaces on the boulder (see Supplementary material).

We isolated beryllium from quartz samples in the cosmogenic nuclide laboratory at Dartmouth College following methods modified after Stone (2001). Samples were measured at the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory (LLNL) with measurement uncertainties less than 3%. We calculated ^{10}Be ages using the CRONUS online calculator (Balco et al., 2008) and the Northeast North American production rate (Balco et al., 2009) found to be accurate for west Greenland by Briner et al. (2012). We used scaling by Desilets and Zreda (2003), Desilets et al. (2006), although using other scaling schemes (e.g. Lal, 1991; Stone, 2000; Dunai, 2001; Lifton et al., 2005) results in less than a 3% difference in ages (Table S2).

3. Results

Nine ^{10}Be ages from the Ørkendalen moraines range from 7.4 ± 0.2 to 6.3 ± 0.2 ka (AMS internal measurement uncertainty) (Table 1). The average age of the Ørkendalen moraines at site 1 is 6.7 ± 0.3 ka ($n = 4$), at site 2 is 7.0 ± 0.3 ka ($n = 3$), and at site 3 is 6.5 ± 0.1 ka ($n = 2$) (Fig. 3). A reduced chi-squared test of these nine ages yields a value of 2.96, indicating that geomorphic factors influencing the ^{10}Be ages are minimal (e.g. Balco and Schaefer, 2006; Balco, 2011). The small variance among the ^{10}Be ages also suggests that the boulders were amply eroded during glacial transport, prior to deposition on the moraines, removing any "inherited ^{10}Be" (e.g. Kelly et al., 2008). An ANOVA test indicates that the mean ages from each of the three sites are not significantly different ($p = 0.2$). Therefore, we present the average of nine ^{10}Be ages (6.8 ± 0.3 ka) as the age of the Ørkendalen moraines.

4. Discussion

The ^{10}Be ages of the Ørkendalen moraines provide the first direct ages on moraines in the Kangerlussuaq region. These ages agree very well with the moraine age determined using bracketing radiocarbon ages (6.8 ± 0.3 cal kyr BP; van Tatenhove et al., 1996b). The corroboration of ^{10}Be and radiocarbon ages indicates that ^{10}Be dating of moraines in this region yields accurate results and provides a useful means to date other moraines in the region.

The age of the Ørkendalen moraines provides an important constraint on the extent of the GrIS during middle Holocene time. Since the Ørkendalen moraines are in places overlain or partially cross cut by LIA moraines, the ice sheet margin must have been inboard of the Ørkendalen moraines between 6.8 ka and the late 19th century. In addition, the LIA advance reached the most extensive ice margin position since middle Holocene time. In contrast, Forman et al. (2007) describe a Neoglacial moraine outboard from the LIA moraines, ~2 km from our site 2. Using optically stimulated luminescence to date loess atop this moraine, Forman et al. (2007) suggest a moraine age of ~2.0 ka. We found no moraines between the Ørkendalen and LIA moraines at any of our study sites and suggest that further study is needed to examine

Table 1
^{10}Be ages and associated metadata of boulders on Ørkendalen moraines at all three locations.

Sample ID	Latitude (°N)	Longitude (°W)	Elevation (masl)	Shielding correction	Thickness (cm)	^{10}Be Conc. (atoms/g)[a]	Uncertainty (atoms/g)[b]	Age (ka)[c]	Uncertainty (ka)[b]
Site 1: Moraine valley									
LL0901	67.105	−50.290	247	0.998	1.8	3.47×10^4	8.17×10^2	6.29	0.15
LL0902	67.103	−50.282	241	0.998	2.6	3.77×10^4	1.08×10^3	6.93	0.20
LL0903	67.101	−50.283	242	0.998	1.8	3.78×10^4	1.12×10^3	6.89	0.21
LL0904	67.092	−50.294	224	0.997	2.6	3.65×10^4	9.74×10^2	6.82	0.18
Site 2: Southeast of Isunnguata Sermia									
LL0906	67.159	−50.102	432	0.999	2.0	4.42×10^4	9.73×10^2	6.74	0.15
LL0907	67.158	−50.104	434	0.996	2.4	4.56×10^4	1.19×10^3	6.99	0.18
LL0908	67.158	−50.105	423	0.977	1.5	4.72×10^4	1.45×10^3	7.39	0.23
Site 3: Southern margin of Isunnguata Sermia, adjacent to the LIA moraines									
LL0909	67.161	−50.119	449	0.998	1.6	4.32×10^4	1.35×10^3	6.46	0.20
LL0911	67.162	−50.116	458	0.984	2.6	4.36×10^4	1.13×10^3	6.61	0.17

[a] All samples were measured using the beryllium standard 07KNSTD (Nishiizumi et al., 2007).
[b] Uncertainty is reported internal AMS uncertainty.
[c] ^{10}Be ages shown assume an erosion rate of 0.0001 cm/yr.

evidence for Neoglacial ice sheet extents in the Kangerlussuaq region.

A comparison of the deglaciation age of the landscape outboard of the late Holocene ice sheet extent in western Greenland shows spatial variability that likely reflects the sensitivity of the ice sheet to climatic changes (Fig. 1a). In many locations the LIA and present-day ice sheet extents are located near each other and we therefore consider deglaciation ages outboard of the outermost late Holocene margin position. At Jakobshavn Isbræ, ~240 km north of Kangerlussuaq, ^{10}Be ages of bedrock outboard of the LIA moraines indicate deglaciation by 7.5 ka (Corbett et al., 2011; Young et al., 2011). This deglaciation age is broadly contemporaneous with that outboard of the LIA moraines near Kangerlussuaq (6.8 ka). In contrast, regions in the north and south of western Greenland experienced deglaciation to the present-day ice margin position by early Holocene time. Near the Qassimiut lobe in southern Greenland (Fig. 1a) ~700 km south of Kangerlussuaq, the ice sheet was at its present-day extent by ~9.5 cal kyr BP (Weidick et al., 2004). Similarly, at Melville Bugt ~900 km to the north of Kangerlussuaq (Fig. 1a), the ice sheet reached its present-day extent by ~9.0 cal kyr BP (Bennike, 2008). This pattern of deglaciation ages outboard of the late Holocene ice margin position may reflect the amount of deglaciation in a region during early to middle Holocene time. Perhaps due to the significant recession in central and south-western Greenland during the HTM the subsequent LIA advance did not reach as far west as the in the north and south (e.g. near Melville Bugt and the Qassimiut Lobe). An alternative hypothesis to explain the pattern of deglaciation ages outboard of the late Holocene ice margin position is that the LIA advance was more extensive in the north and south. Further research is needed to test these hypotheses.

5. Conclusions

New ^{10}Be ages demonstrate that the Ørkendalen moraines were deposited at ~6.8 ± 0.3 ka, marking a readvance or stabilization during recession of the ice sheet subsequent to the last ice age. These ^{10}Be ages are consistent with prior Ørkendalen moraine age estimates based on bracketing radiocarbon ages (van Tatenhove et al., 1996b). Together, the ^{10}Be and radiocarbon ages support an accurate and precise age for the extent of the GrIS during middle Holocene time. The stratigraphic relationship between the Ørkendalen and LIA moraines in the study area suggests that the GrIS was inboard of the Ørkendalen moraines between ~6.8 ka and the late 19th century and that the LIA was the most extensive advance since 6.8 ka. The position and age of the Ørkendalen moraines provide useful data for calibrating ice sheet models.

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Appendix A. Supplementary material

Supplementary materials related to this article can be found online at http://dx.doi.org/10.1016/j.quascirev.2012.07.021.

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