Quaternary Science Reviews xxx (2015) 1–10

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

# $^{10}$Be dating reveals early-middle Holocene age of the Drygalski Moraines in central West Greenland

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ARTICLE INFO

*Article history:*
Received 5 February 2015
Received in revised form
26 August 2015
Accepted 28 August 2015
Available online xxx

*Keywords:*
Cosmogenic nuclide exposure dating
Greenland Ice Sheet
Proglacial-threshold lake
Holocene

ABSTRACT

We reconstruct the history of the Greenland Ice Sheet margin on the Nuussuaq Peninsula in central West Greenland through the Holocene using lake sediment analysis and cosmogenic $^{10}$Be exposure dating of the prominent Drygalski Moraines. Erratics perched on bedrock outboard of the Drygalski Moraines constrain local deglaciation to ~9.9 ± 0.6 ka (n = 2). Three Drygalski Moraine crests yield mean $^{10}$Be ages of 8.6 ± 0.4 ka (n = 2), 8.5 ± 0.2 ka (n = 3), and 7.6 ± 0.1 ka (n = 2) from outer to inner. Perched erratics between the inner two moraines average 7.8 ± 0.1 ka (n = 2) and are consistent with the moraine ages. Sediments from a proglacial lake with a catchment area extending an estimated 2 km beneath (inland of) the present ice sheet terminus constrain an ice sheet minimum extent from 5.4 ka to 0.6 ka. The moraine chronology paired with the lake sediment stratigraphy reveals that the ice margin likely remained within ~2 km of its present position from ~9.9 to 5.4 ka. This unexpected early Holocene stability, preceded by rapid ice retreat and followed by minimum ice extent between ~5.4 and 0.6 ka, contrasts with many records of early Holocene warmth and the Northern Hemisphere summer insolation maximum. We suggest ice margin stability may instead be tied to adjacent ocean temperatures, which reached an optimum in the middle Holocene.



## 1. Introduction

Concerns about global climate change involve the response of climatically sensitive regions like the Arctic, including response of the Greenland Ice Sheet (GrIS), to increases in global temperature (Vaughan et al., 2013). The GrIS is estimated to contain the equivalent of ~7.4 m of global sea level rise (Morice et al., 2012) and ~10% of the global population lives in low elevation coastal areas, implying high potential for future socio-economic impact should sea level rise continue (Oliver-Smith, 2009). Reconstructing past ice sheet margins is useful for assessing how the GrIS has responded to past climate changes (such as warm and cold times during the Holocene), as well as for testing ice sheet models used for projections of future sea level rise (Applegate et al., 2012).

Fundamental gaps in our knowledge of GrIS fluctuations throughout the Holocene hamper our ability to assess its response to past climate change. Records of both temperature and ice margin fluctuations throughout the Holocene are increasingly documented, but geomorphic evidence of ice sheet extent during the middle-to-late Holocene is sparse because it is often buried beneath the present extent of the GrIS (Funder et al., 2011). The paucity of moraines preserved from pre-Little Ice Age (LIA; 1200–1900 AD) middle-to-late Holocene glaciation limits our understanding of GrIS margin response during a period of climate transition from warmer to cooler conditions (Kaufman et al., 2004; Marcott et al., 2013).

There are few locations in Greenland that contain ice sheet moraines mapped outboard of the LIA extent that are associated with or dated to the middle or late Holocene (Weidick, 1968;

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http://dx.doi.org/10.1016/j.quascirev.2015.08.034
0277-3791/

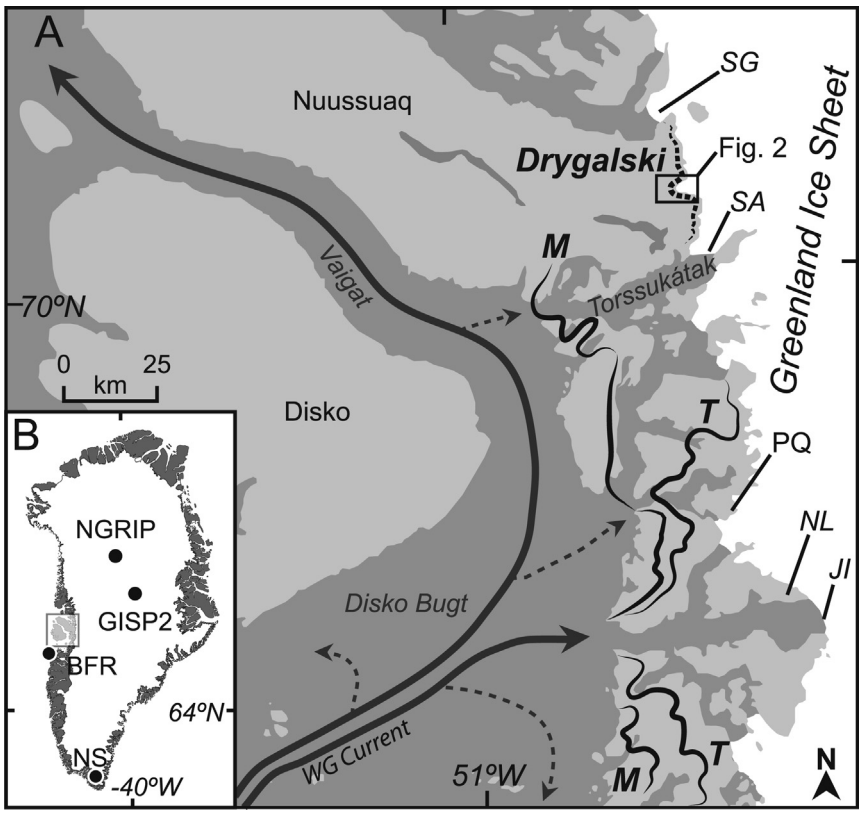


**Fig. 1.** A) Central West Greenland; thick black lines are Drygalski (dashed) and Fjord Stade [solid; Marrait = M, Tasiussaq = T] Moraines. Sites referred to in the text are: SG = Store Gletscher; SA = Sermeq Avannarleq; PQ = Paaqitsoq; NL = North Lake; JI = Jakobshavn Isbræ. Arrows show West Greenland (WG) Current. Inset (B) shows map of Greenland showing locations of ice cores NGRIP and GISP2, benthic foraminifera record (BFR; Perner et al. (2013) and ice margin record (NS, Larsen et al., 2011).

Bennike and Weidick, 2001; Bennike and Sparrenbom, 2007; Forman et al., 2007; Winsor et al., 2014), one of which is the Drygalski Moraine system in central West Greenland (Fig. 1; Kelly, 1980). The Drygalski Moraines were first described in the late 1800s by a German group led by Erich von Drygalski (von Drygalski et al., 1897). The Drygalski Moraines were deposited outboard of LIA moraines, which are interpreted to grade to present day sea level at Store Gletscher to the north and Torssukátak to the south, indicating a maximum age of ~5 ka based on relative sea level curves (Weidick, 1968). To date there have been no attempts to directly date the Drygalski Moraines. The assignment of the Drygalski Moraines to late Holocene glaciation is important to test because a late Holocene age would make the Drygalski Moraines anomalously young compared to the early Holocene age of moraines present in the Disko Bugt region (e.g., Young et al., 2013a).

We reconstruct the Holocene GrIS history on inner Nuussuaq using radiocarbon and cosmogenic $^{10}$Be exposure dating (hereafter referred to as $^{10}$Be dating). The main objective of this study is to directly date the Drygalski Moraines to verify or refute previous estimates that they were deposited during the middle or late Holocene (Weidick, 1968). Two potential late Holocene moraines may be comparable to the Drygalski Moraines: the Narsarsuaq moraines in southern Greenland (>1.5 ka; Winsor et al., 2014) and the middle-Holocene moraines dated by Lane et al. (2014) in the Uummannaq Fjord system north of Nuussuaq. Alternatively, the Drygalski Moraines may be analogous to the Ørkendalen (~6.8 ka) or Fjord Stade (Tasiussaq ~8.2 ka; and Marrait ~9.3 ka; Fig. 1) moraine systems dated south of the Drygalski Moraines in West Greenland (Levy et al., 2012; Young et al., 2013a). Determining the age of the Drygalski Moraines and assessing the temporal significance of their deposition offers an opportunity to add to our understanding of the spatial variability of ice margin change during the Holocene.

## 2. Setting

Nuussuaq (peninsula) is located to the north of Vaigat Straight and Disko Island in central West Greenland. Bedrock at this location consists of Precambrian basement dominated by gneissic lithologies (Weidick and Bennike, 2007). Nuussuaq is bounded by relatively fast flowing (several kilometers per year), marine-terminating glaciers to the north and south (Fig. 1; Rignot and Mouginot, 2012). In contrast, the GrIS margin that deposited the Drygalski Moraines is a relatively slow-flowing (10 s of meters per year; Rignot and Mouginot, 2012) small land-terminating lobe we refer to as the Nuussuaq Lobe (informal name) that lies along the right-lateral flank of the major marine outlet glacier Sermeq Avannarleq. The Nuussuaq Lobe terminus is bordered by a proglacial lake (informally called Newspaper Lake) and is surrounded by the Drygalski Moraines (Fig. 2).

The Drygalski Moraines include at least four moraine ridges near the present ice margin that are outboard of subdued (only few m in relief), unvegetated historical moraines (Weidick, 1968; Fig. S1). It is difficult to ascertain the number of discrete Drygalski Moraine crests that were originally deposited due to the present extent of the Nuussuaq Lobe, which currently truncates parts of what may have been previously continuous, and additional, moraine ridges. A number of these moraines have been breached in places by meltwater channels that feed into Newspaper Lake (Fig. 2). The Drygalski moraines range from ~10 to 30 m in height and include some

Please cite this article in press as: Cronauer, S.L., et al., $^{10}$Be dating reveals early-middle Holocene age of the Drygalski Moraines in central West Greenland, Quaternary Science Reviews (2015), http://dx.doi.org/10.1016/j.quascirev.2015.08.034