Response of the southern Greenland Ice Sheet during the last two deglaciations

Anders E. Carlson* Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA
Joseph S. Stoner College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA
Jeffrey P. Donnelly Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA
Claude Hillaire-Marcel GEOTOP, Université du Québec à Montréal, CP 8888, Montreal, Quebec H3C 3P8, Canada

ABSTRACT

The retreat of the southern Greenland Ice Sheet (GIS) during the last deglaciation (Termination I: TI) is poorly dated by conventional means; there is even greater uncertainty about the penultimate deglaciation (Termination II: TII), leading to the assumption that the southern GIS has a significant lag in its response to deglacial warming. Here we use geochemical terrestrial sediment proxies ([Fe] and [Ti]) from a well-studied southern Greenland marine sediment sequence to examine the behavior of the southern GIS during TI and TII. Our records show that during TI and TII the southern GIS response was essentially synchronous with deglacial North Atlantic warming, implying greater climate sensitivity than previously assumed. During TI, elevated ablation lasted ~5 k.y., whereas ablation remained elevated for ~12 k.y. during TII, suggesting a reduced southern GIS during TII that contributed a significant fraction of the higher sea level during the subsequent interglacial.

Keywords: southern Greenland Ice Sheet, deglaciation, sea level, ice sheet response.

INTRODUCTION

Determining the timing and magnitude of Northern Hemisphere ice sheet responses to past climate changes provides valuable insight for predicting the future response of the Greenland Ice Sheet (GIS). Whereas other ice sheets have moraine records that can be dated by conventional means (e.g., Dyke, 2004; Rinterknecht et al., 2006), the GIS extended onto the continental shelf at glacial maximums and much of its deglacial record is now submerged (Fig. 1) (e.g., Bennike and Björck, 2002). The chronology for the GIS following the Last Glacial Maximum (LGM, ca. 21 ka B.P.) is based on terrestrial and raised marine radiocarbon dates. Such dates only provide a minimum estimate of when the ice sheet retreated off the continental shelf, and may reflect the migration of vegetation to Greenland rather than the timing of deglaciation (Bennike and Björck, 2002). These dates have led to the general assumption that GIS retreat lagged behind other Northern Hemisphere ice sheets and occurred during the early Holocene (Bennike and Björck, 2002; Tarasov and Peltier, 2002). However, one radiocarbon date from the southern tip of Greenland and marine records from east Greenland suggest that the southern to eastern GIS may have retreated earlier (Nam et al., 1995; Andrews et al., 1997; Bennike and Björck, 2002).

Recent glaciological studies have discovered an acceleration of the GIS and increasingly negative mass balance, perhaps in response to global warming, suggesting a greater sensitivity to climate change than previously thought (Alley et al., 2005). Furthermore, the last interglacial (ca. 130–120 ka B.P.) Arctic climate was ≥2 °C warmer than present (Otto-Bliesner et al., 2006), and sea level was 4–6 m higher than present (Thompson and Goldstein, 2005). Ice sheet models and Greenland ice core, marine sediment magnetic grain size, and pollen records suggest a diminished last interglacial GIS that contributed 2.2–5.5 m of the higher sea level with significant southern GIS retreat (sGIS in Fig. 1) (Koerner, 1989; Stoner et al., 1995; Cuffey and Marshall, 2000; Hillaire-Marcel et al., 2001; Tarasov and Peltier, 2003; Lhomme et al., 2005; Otto-Bliesner et al., 2006). Here we use [Ti] and [Fe] records from the Eirik Drift off southern Greenland (Fig. 1) to examine the response of the southern GIS during the last (TI, ca. 21–10 ka B.P.) and penultimate (TII, ca. 136–126 ka B.P.) deglaciations.

METHODS

We measured [Ti], [Fe], [Ca], and [Sr] in core MD99–2227 (Fig. 1) using an ITRAX model X-ray fluorescence core scanner at 400–1000 µm intervals and smoothed to 1 cm (for age model construction see Fig. DR1 and Table DR1 in the GSA Data Repository[1]). Ca and Sr reflect the input of biogenic and detrital carbonate. Ti and Fe are derived from continental sources and reflect bulk terrestrial sediment input. Fe is susceptible to redox changes, but the agreement between Fe and Ti ($R^2 = 0.60$) indicates that redox changes have a lesser impact than sediment supply on [Fe]. We remove the dilution effects of biogenic and detrital carbonate by determining the inverse linear relationship between Ca-Ti and Ca-Fe (Figs. DR2 and DR3), and dividing [Ti] and [Fe] by these values to calculate changes in [Ti] and [Fe] relative to [Ca].

The two possible terrestrial sediment sources to the Eirik Drift are the southern Greenland Precambrian shield and sediment transported in the Western Boundary Under Current (WBUC), including Tertiary basalts of Iceland and east Greenland (Fig. 1) (Fagel et al., 2002). We determined that the main sediment source is the southern Precambrian shield by comparing [Ti] and [Fe] signals, [Ca] and %$CaCO_3$, and principal component analyses of [Ti], [Fe], [Ca], and [Sr] (Figs. DR3 and DR4). We note that the WBUC was reduced during TI, TII, and the last interglacial (Hillaire-Marcel et al., 2001). Thus the geochemical changes in our records likely do not reflect changes in the amount of WBUC-delivered sediment, but rather changes in the input of proximally derived sediment from southern Greenland.

To interpret the Ti and Fe records, sediment transport mechanisms from southern Greenland to the core site need to be identified. MD99–2227 is located off of the continental shelf and would not receive significant amounts of direct southern GIS marginal sediment from till deposition and subglacial meltwater discharge (Fig. 1). Thus we interpret the Ca-corrected [Ti] and [Fe] as a proxy of terrestrial sediment carried by summer meltwater from southern GIS ablation and precipitation runoff (i.e., Hasholt, 1996) with occasional ice rafted debris, similar to an interpretation of Lamy et al. (2004) for [Fe] marine records of Patagonian Ice Sheet behavior (see the Data Repository for further discussion). This interpretation is supported by observations of modern ice cap retreat from

*Current address: Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53703, USA; E-mail: acarlson@geology.wisc.edu.

[1]GSA Data Repository item 2008090, detailed methods, core chronology, Figs. DR1–DR4 and Table DR1, and discussion of sediment source interpretations, supplementary figures and core age model construction, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

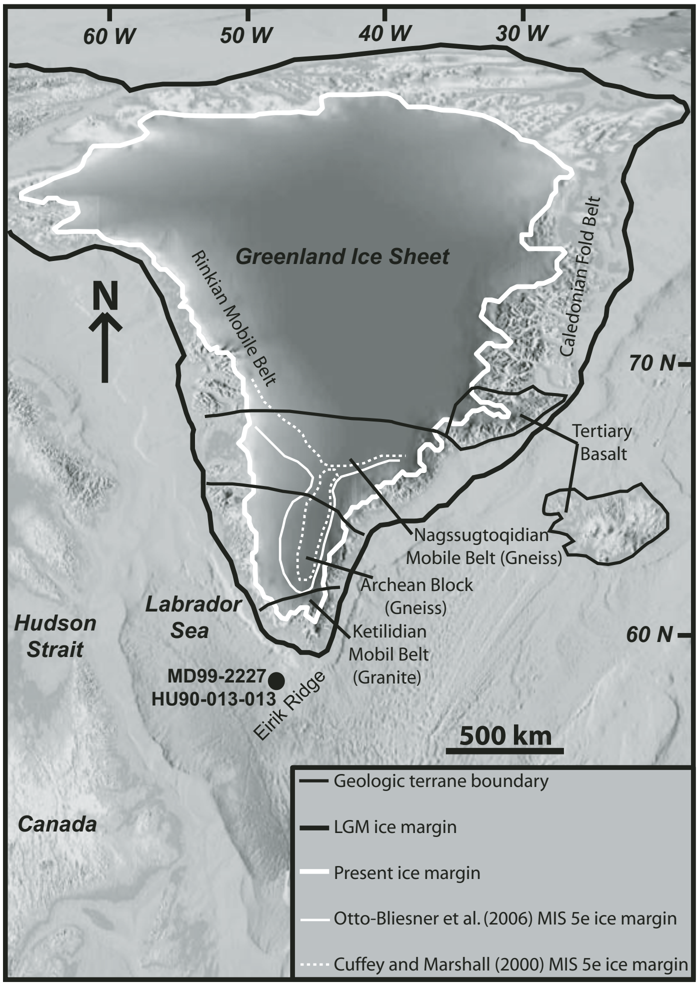

Figure 1. Core locations, aerial extent of Greenland Ice Sheet (GIS), and geologic terrane boundaries (Fagel et al., 2002). Core MD99–2227 (58°12.46′N, 48°22.38′W, 3460 m water depth) and HU90–013–013 (58°13.00′N, 48°22.00′W, 3380 m water depth) are from the Eirik Drift in the southeastern Labrador Sea (black dot). Last Glacial Maximum (LGM) (Dyke, 2004), present, and marine isotope stage (MIS) 5e ice margins are indicated. Otto-Bliesner et al. (2006)—2.2 m of sea-level rise from GIS; Cuffey and Marshall (2000)—4 m of sea-level rise from GIS.

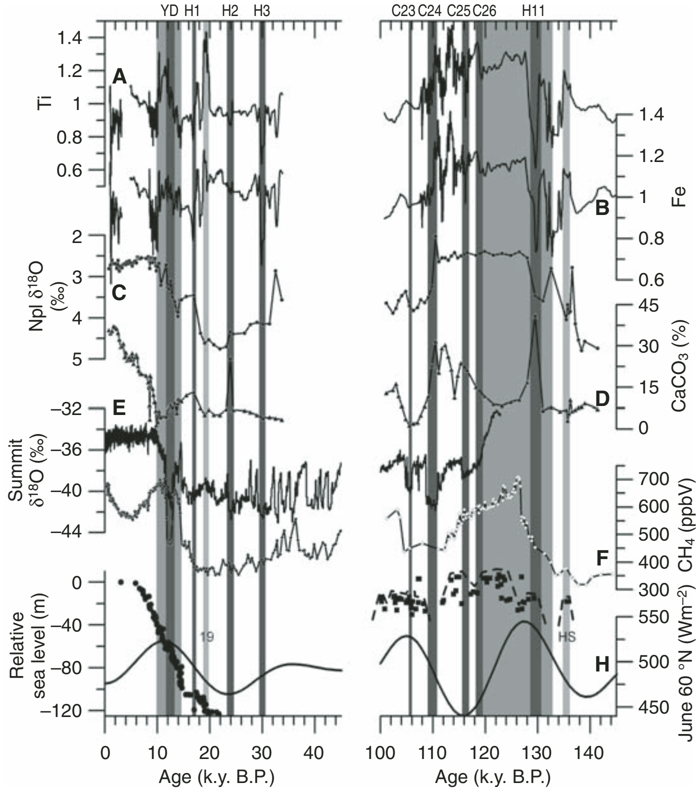

Figure 2. Southern Greenland Ice Sheet (GIS) [Ti], [Fe], and paleoclimate records for the last two deglaciations (left x-axis is last deglaciation, TI, right x-axis is TII). A: MD99–2227 [Ti] (upper black line with y-axis to left). B: MD99–2227 [Fe] (lower black line with y-axis to the right). C: MD99–2227 *Neogloboquadrina pachyderma sinistral* (Npl) δ^{18}O (black line with round symbols). D: MD99–2227 percent $CaCO_3$ (black line with triangle symbols). E: Summit Greenland δ^{18}O from Greenland Ice Sheet Project 2 (GISP2) (left) and North Greenland Ice Core Project (NGRIP) (right) (black step plot) (Blunier and Brook, 2001; North Greenland Ice Core Project Members, 2004). F: Atmospheric [CH_4] (black line with diamond symbols) (Petit et al., 1999; Monnin et al., 2001). G: Relative sea level for TI (black circles) (Clark and Mix, 2002) and TII (black squares, dashed interpretive lines) (Thompson and Goldstein, 2005). H: June insolation at 60° N (black line) (Berger and Loutre, 1991). Dark gray bars denote cold events: Younger Dryas (YD), H1–H3, H11, and C23–C26. Medium gray bars denote extended periods of elevated runoff and major ice margin retreat. Light gray bars denote 19 ka B.P. sea-level rise (19) and the initial sea-level highstand ca. 136 ka B.P. (HS).

the Little Ice Age when the major flux of sediment to the ocean occurred during ice retreat (Hallet et al., 1996). At maximum ice extent, the southern GIS produced sediment by erosion, but much of it was trapped under ice, reducing its delivery to the ocean to ice rafting with some proglacial stream transport. Southern GIS retreat exposed glacial sediment on the continental shelf, increasing the amount of sediment that meltwater streams could transport to the ocean. Further retreat inland exposed sediment in valleys and on uplands, supplying more sediment to the streams (Hallet et al., 1996). Thus the availability of sediment and amount of meltwater are linked to summer ablation and ice retreat. In inferring changes in southern GIS mass from ablation, we note that possible increased ice accumulation from warming is overwhelmed by ablation (e.g., Alley et al., 2005), resulting in net ice mass loss.

RESULTS AND DISCUSSION

Geochemical results from MD99–2227 are illustrated in Figures 2 and 3. In many ways, they mimic changes in magnetic grain size and concentration in the adjacent core HU90–013–013 (Stoner et al., 1995). The reductions in Ti and Fe ca. 17, 30, and 129 ka B.P. are in agreement with the timing of Heinrich events (H) 1, 3, and 11, suggesting decreased summer ablation in response to reduced Atlantic meridional overturning circulation and northward heat transport with attendant sea ice extension (McManus et al., 2004) (Figs. 2 and 3). Ti and Fe reductions at 31 and 33 ka B.P. may also correspond with North Atlantic cooling. There is not a clear response to H2 ca. 24 ka B.P., but summer ablation may be less susceptible to cooling in an already cold climate.

The increases in Ti and Fe centered ca. 18, 19 and 136 ka B.P. correspond with increases in magnetic grain size (Stoner et al., 1995) and are concurrent with an early deglacial sea-level rise ca. 19 ka B.P. (Clark et al., 2004) and a sea-level highstand ca. 136 ka B.P. (Thompson and Goldstein, 2005) (Fig. 2G). Because the southern GIS extended onto the shelf at glacial maxima, these Ti and Fe increases may reflect the unpinning of the southern GIS marine margin with increased sediment outflow and iceberg discharge, in response to sea-level rise. At least during TI, Ti and Fe started to increase prior to the 19 ka B.P. rise, suggesting that some of the increase may be from enhanced ablation in response to early deglacial warming. Ice rafted debris and planktonic δ^{18}O records off east Greenland

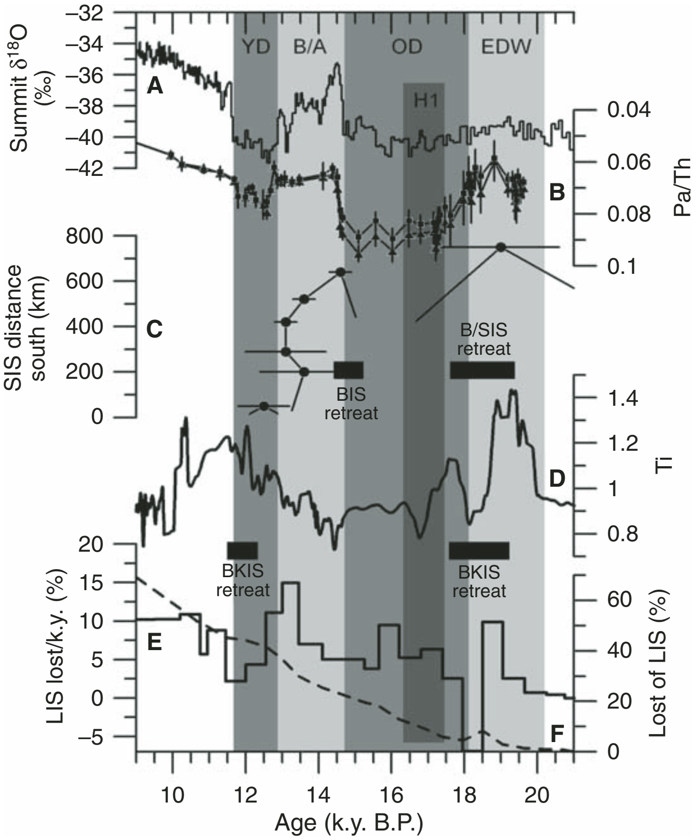

Figure 3. Greenland $\delta^{18}O$, Atlantic meridional overturning circulation (AMOC), and Northern Hemisphere ice sheet records. A: Summit Greenland $\delta^{18}O$ (black step plot) (Blunier and Brook, 2001). B: $^{231}Pa/^{230}Th$ record from North Atlantic (proxy of AMOC strength) (McManus et al., 2004). C: Scandinavian Ice Sheet (SIS) southern margin ^{10}Be moraine record (black with circle symbols): distance south (km) from just north of Younger Dryas moraine (Rinterknecht et al., 2006). Black boxes show period of elevated runoff from SIS and British Ice Sheet (BIS) (B/SIS) (Menot et al., 2006) and BIS retreat (McCabe and Clark, 1998; Clark et al., 2004). D: Greenland Ice Sheet (GIS) MD99–2227 [Ti] (black line). Black boxes show timing of Barents-Kara Sea Ice Sheet (BKIS) retreat (Svendsen et al., 2004). E: Rate of Laurentide Ice Sheet (LIS) retreat in percent of area lost per k.y. (black step plot) (derivative of F) (calculated from Dyke, 2004). F: Percent area lost of LIS (gray dashed line) (calculated from Dyke, 2004). Light gray bars denote early deglacial warming (EDW) and Bølling/Allerød (B/A). Medium gray bars denote Oldest Dryas (OD) and Younger Dryas (YD) cold events. Dark gray bar denotes H1.

also suggest eastern GIS retreat commencing 20–18 ka B.P. (Nam et al., 1995; Andrews et al., 1997), indicating that this early response was not restricted to the southern GIS.

Following a period of reduced runoff associated with reduced Atlantic meridional overturning circulation from ca. 18–14.7 ka B.P. during the Oldest Dryas, southern GIS Ti and Fe increased ca. 14.7 ka B.P. (Fig. 3), coincident with an increase in magnetic grain size (Stoner et al., 1995) and the deposition of sediment from radiogenic terranes (Fagel et al., 2002). These increases in terrestrial sediment likely reflect increased southern GIS ablation and runoff in response to increased Atlantic meridional overturning circulation with attendant sea ice retreat and Bølling warming, implying a tight coupling of southern GIS ablation, Atlantic meridional overturning circulation, and climate (Figs. 2 and 3). The timing of increased ablation and runoff is in agreement with the oldest minimum limiting radiocarbon date from southern Greenland, which indicates retreat initiating sometime before ca. 14.1 ka B.P. (Bennike and Björck, 2002). Ti and Fe remained elevated until ca. 10 ka B.P., suggesting that southern GIS retreat was mostly complete by ca. 10 ka B.P., with deglaciation lasting ~5 k.y.

In our records, steady Ti and Fe increases during the Younger Dryas cold event (12.9–11.5 ka B.P.) (Fig. 2) suggest that North Atlantic cooling and reduced Atlantic meridional overturning circulation of the interval (Fig. 3) did not significantly affect southern GIS ablation. Inferences from the eastern GIS also suggest retreat during this interval (Williams, 1993; Jennings et al., 2006), and climate records from southern and eastern Greenland indicate warm and mild summer conditions during the Younger Dryas (Williams, 1993; Björck et al., 2002), conducive to increased summer ablation. The different southern GIS responses to Oldest Dryas and Younger Dryas cooling may reflect the magnitude of Atlantic meridional overturning circulation reduction, with the greater reduction of the Oldest Dryas having a greater impact on summer ablation than the lesser reduction of the Younger Dryas (Fig. 3).

Comparison between our Ti and Fe records and other North Atlantic ice sheet records (Laurentide, Scandinavian, British, and Barents-Kara Ice Sheets) (McCabe and Clark, 1998; Bowen et al., 2002; Dyke, 2004; Clark et al., 2004; Svendsen et al., 2004; Rinterknecht et al., 2006; Menot et al., 2006) suggests that all North Atlantic ice sheets were in retreat by 20–19 ka B.P., likely in response to initial North Atlantic warming following the LGM (Fig. 3). This retreat culminated in the 19 ka B.P. sea-level rise (Clark et al., 2004), indicating that all North Atlantic ice sheets contributed in some magnitude to this rise (Figs. 2G and 3). North Atlantic surface freshening from this retreat probably caused the reduction in Atlantic meridional overturning circulation and Oldest Dryas cooling ca. 18 ka B.P. (Clark et al., 2004) (Fig. 3). Following ice sheet readvances or at least reduced retreat during this event, increased Atlantic meridional overturning circulation with Bølling warming ca. 14.7 ka B.P. caused ice sheets to resume retreat. The only ice sheets with a clearly discerned response to Younger Dryas cooling (Scandinavian, British, and Barents-Kara Ice Sheets) are located at the end of the North Atlantic drift in the eastern North Atlantic–Arctic (Bowen et al., 2002; Svendsen et al., 2004; Rinterknecht et al., 2006), where a reduction in northward heat transport from reduced Atlantic meridional overturning circulation would probably have a greater impact on ice sheet mass balance than in the western North Atlantic. Therefore, while North Atlantic ice sheets may have responded differently to cooling depending on their geographic distribution relative to heat transport, they all responded in concert to increases in Atlantic meridional overturning circulation and attendant climate warming of the last deglaciation.

During TII, the major period of elevated Ti and Fe and inferred southern GIS retreat began ca. 132 ka B.P. With the exception of a reduction from 130 to 128 ka B.P., Ti and Fe remained elevated but relatively constant for the next ~12 k.y., suggesting high but steady runoff, which may be reflected in the consistently light planktonic $\delta^{18}O$ (Fig. 2C) and decreased surface salinity of the Labrador Sea (Hillaire-Marcel et al., 2001). This extended period of freshwater input reduced surface water mass density, not allowing winter convection and explaining the lack of Labrador deep seawater formation during this interglacial (Hillaire-Marcel et al., 2001). After ca. 120 ka B.P., Ti and Fe gradually decreased, suggesting reduced southern GIS ablation that followed the cooling trend into the next glacial period with four Ti-Fe oscillations possibly in response to North Atlantic climate fluctuations (Figs. 2E, 2F, and 2H). The longer period of elevated Ti and Fe during TII (~12 k.y.) relative to TI (~5 k.y.) (Fig. 2) indicates greater southern GIS retreat during TII, in agreement with sediment magnetic, palynological, and ice core records (Koerner, 1989; Stoner et al., 1995; Hillaire-Marcel et al., 2001), and ice sheet models (Fig. 1) (e.g., Lhomme et al., 2005; Otto-Bliesner et al., 2006). This further confirms that the GIS probably contributed a substantial portion of the higher sea level during this interglacial under enhanced boreal summer insolation forcing (Figs. 2G, 2H).

While Greenland ice core records do not extend back to TII, we can estimate Summit Greenland $\delta^{18}O$ records using atmospheric $[CH_4]$ from Antarctic ice cores, given the correlation between Greenland $\delta^{18}O$ and atmospheric $[CH_4]$ (Blunier and Brook, 2001) (Figs. 2E, 2F). This correlation suggests that the initial TII increases in Ti and Fe were coincident with warming of the North Atlantic region ca. 132 ka B.P. (Fig. 2). Peak North Atlantic warming of ≥2 °C (Otto-Bliesner et al., 2006) may correlate with the interglacial CH_4 peak ca. 127 ka B.P., suggesting that the inferred peak in southern GIS ablation during TII corresponds with maximum interglacial warming. These correlations imply a rapid southern GIS response to warming similar to the radiocarbon-dated responses during TI, suggesting that the southern GIS responded essentially synchronously to past climate warming on both orbital and millennial time scales.

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