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Widespread Antarctic glaciation during the Late Eocene

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ABSTRACT

Marine sedimentary rocks drilled on the southeastern margin of the South Orkney microcontinent in Antarctica (Ocean Drilling Program Leg 113 Site 696) were deposited between ~36.5 Ma to 33.6 Ma, across the Eocene–Oligocene climate transition. The recovered rocks contain abundant grains exhibiting mechanical features diagnostic of iceberg-rafted debris. Sand provenance based on a multi-proxy approach that included petrographic analysis of over 275,000 grains, detrital zircon geochronology and apatite thermochronometry rule out local sources (Antarctic Peninsula or the South Orkney Islands) for the material. Instead the ice-transported grains show a clear provenance from the southern Weddell Sea region, extending from the Ellsworth–Whitmore Mountains of West Antarctica to the coastal region of Dronning Maud Land in East Antarctica. This study provides the first evidence for a continuity of widespread glacier calving along the coastline of the southern Weddell Sea embayment at least 2.5 million yrs before the prominent oxygen isotope event at 34–33.5 Ma that is considered to mark the onset of widespread glaciation of the Antarctic continent.

1. Introduction

The period leading up to the glaciation of Antarctica remains poorly understood. Whilst there is a general consensus that the onset of continent-wide glaciation in Antarctica occurred around the Eocene–Oligocene Transition (EOT) during a prominent oxygen isotope excursion at 34–33.5 Ma it is debatable as to whether a single or combination of drivers and feedbacks collectively drove the climate transition. The oxygen isotope event is manifested by a sharp transient increase in deep-sea benthic foraminiferal δ^{18}O values reflecting cooling and a major growth in global ice volume (Coxall et al., 2005; Zachos et al., 2001), a significant sea-level fall that implies major ice build-up in Antarctica (Miller et al., 2005; Stocchi et al., 2013), deposition of ice rafted debris (IRD) on the seabed around Antarctica (Zachos et al., 1992) and geochemical (Basak and Martin, 2013; Passchier et al., 2013), and clay and mineralogical changes (Ehrmann and Mackensen, 1992; Houben et al., 2013) that show a shift from chemical to physical weathering of terrigenous detritus supplied from the Antarctic continent to the Southern Ocean.

Work by Scher et al. (2014) on Middle to Late Eocene sediments from Ocean Drilling Program (ODP) Site 738 on the Kerguelen Plateau (Fig. 1) produced a high-resolution benthic foraminiferal δ^{18}O record alongside a Nd isotope record, for the clay and silt-sized (<63 μm) terrigenous fraction. The data identified a transient rise in benthic δ^{18}O values at c. 37.3 Ma that the authors interpreted as a possible episode of ice sheet expansion and referred to as the PrOM event (Priabonian oxygen isotope maximum). During this excursion radiogenic εNd values of terrigenous sediment were lower and consistent with an increased contribution of fine-grained sediment from old source terrains such as Prydz Bay and/or Wilkes Land (Fig. 1). It was proposed that these sediments were most likely of glaciofluvial origin and therefore ice was present in East Antarctic drainage basins at that time. However, the nature of these proxy data cannot tie the sediments to specific source areas and there is no direct evidence to completely rule out fluvial transport, e.g. along the Lambert Graben (Fig. 1) and/or transport by bottom currents.

Despite some evidence for Eocene ice, it is clear that considerable uncertainties remain about the nature and geographical extent of the earliest ice on Antarctica due to the limitations of geochemical proxy records in defining ice volume and of far-field proxy records in locating ice-sheet build-up. This has steered researchers to explore sediment lithologies, grain sizes and microtexture data in more proximal records along the Antarctic mar-

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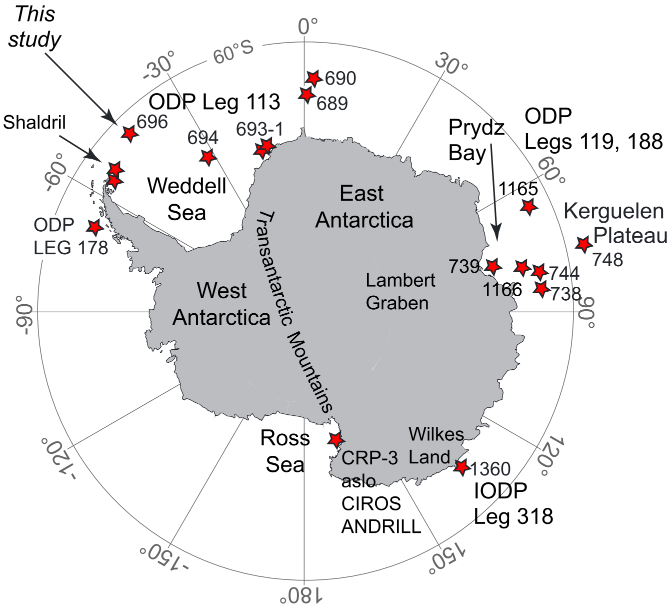

Fig. 1. Present-day locations of areas, where major studies on marine sediments have been undertaken for reconstructing Antarctic ice-sheet history during the Palaeogene and/or Neogene.

gin. The studies have found evidence of glacigenic components in marine sediments, such as diamictons deposited on the shelf, glacial microtextures on sand grains in shelf sediments and IRD in deep-sea sediments, that predate the EOT (e.g. in Prydz Bay, on Maud Rise and Kerguelen Plateau (Fig. 1) (Barron et al., 1991; Breza and Wise, 1992; Ehrmann and Mackensen, 1992; Strand et al., 2003). Based on these findings the authors argued for mountainous glaciers reaching sea level during the Middle to Late Eocene, i.e. significantly prior to the marked shift in oxygen isotope values, but some of the evidence was disputed because of ambiguous depositional settings (e.g. interpretation of diamictons either as subglacial tills or debris flow deposits), age model uncertainties (e.g. the biostratigraphic age used in Strand et al. (2003) are loosely given as lower Oligocene to upper Eocene) and possible down-hole contamination of IRD records with significantly younger IRD.

The most recent proximal data for the state of early ice comes from the Cape Roberts Drilling Project (CRP) which investigated a shallow-water glaciomarine sedimentary succession in the Victoria Land Basin (CRP-3 on Fig. 1) on the western Ross Sea shelf and found a major increase in glacially derived sediments at around 33 Ma (Barrett, 2007). The well-dated CRP-3 drill core suggests a stable continental-scale West Antarctic Ice Sheet (WAIS) calving at the coastline only after 32.8 Ma (Galeotti et al., 2016). There is evidence for orbital pacing of glacial advance and retreat cycles between 34 and 31 Ma, indicating that the nascent Antarctic ice was strongly sensitive to local insolation forcing. The stabilization of continental scale WAIS at 32.8 Ma appears to have been sensitive to crossing a CO_2 threshold, although the precise CO_2 threshold for ice expansion is subject to huge uncertainties (Anagnostou et al., 2016; Gasson et al., 2014). Furthermore, the study by Galeotti et al. (2016) only constrained a part of the WAIS proximal to the coastline in the western Ross Sea. Consequently, the location and extent of Late Palaeogene glacial ice in Antarctica, and the origins of the much larger East Antarctic Ice Sheet (EAIS) remains unresolved.

To improve understanding of the state of the Antarctic cryosphere we studied the provenance of Late Eocene to Oligocene marine sediments from ODP Leg 113 Site 696 drilled on the southeastern margin of the South Orkney Microcontinent (SOM; Fig. 2). Paleolatitude reconstructions based on a reference frame relative to the Earth's spin axis (van Hinsbergen et al., 2015) show that in the Late Eocene the SOM was 600–800 km south of its present-day location and part of the northern tip of the Antarctic Peninsula arc-fore-arc terrane (Fig. 3) before Eocene rifting and opening of the Powell and Jane Basins (Fig. 2) caused the geographic isolation of the SOM (Eagles and Livermore, 2002; Eagles and Jokat, 2014). Whilst the changes in location of the SOM are reasonably well constrained this is not the case for Drake Passage opening which involved the dispersal of a mosaic of small continental blocks that once formed the land bridge connecting South America with the Antarctic Peninsula.

This Eocene rifting resulted in the opening of a newly formed rift basin capturing the bulk of the terrigenous detritus shed from the northern Antarctic Peninsula, confining sedimentation on the SOM shelf to local sources and potentially iceberg-rafted debris (IBRD) from distal sources. The latter is likely because at present the SOM is located within ‘iceberg alley’. Today icebergs calved from the East Antarctic Ice Sheet and released into the Antarctic Coastal Current, a comparatively fast, shallow westward current, mix with icebergs derived from West Antarctica in the cyclonic Weddell Gyre, which transports the icebergs northwards into the Scotia Sea (Fig. 2). A similar circulation system with a proto-Weddell Gyre, similar to today, probably existed already during the Eocene. This is suggested by general circulation model experiments of Eocene paleoceanographic circulation that replicate the spatial distribution and relative abundance patterns and endemism amongst fossil Transantarctic flora (Huber et al., 2004; Bijl et al., 2011).

2. Material

Site 696 was drilled during ODP Leg 113 in 1987. Located on the southeastern margin of the SOM at a water depth of 650 m drilling passed through a sequence of hemipelagic, and pelagic terrigenous sediments deposited between the Late Eocene and the Quaternary (Barker et al., 1988; Wei and Wise, 1990). Despite of only 27% core recovery the oldest part of the drilled sequence is well represented. This study focuses on the shallow marine, sandy-silty mudstones from the lowermost lithological sub-Units VII C and D between 577 m below seafloor and the base of the hole at 646 m.b.s.f. (Fig. 4). Age constraints were established through calcareous nannofossil stratigraphy during the time of drilling (Wei and Wise, 1990) and recently updated by Houben et al. (2013) (Fig. 5). Based on the first consistent occurrence of *Isthmolithus recurvus* and presence of *Reticulofenestra bisecta* the latter authors conservatively estimated the base of the drilled interval to be 36.5 Ma old although the sequence could be as old as 37.6 Ma. The youngest samples examined in this study (52R and 51R) are below core 55R at 569.4 mbsf, which is dated to 33.6 Ma based on the first consistent occurrence of the dinocyst *Malvinia escutiana*. Sample 51R yielded Middle Miocene diatoms (*Denticulopsis lauta*, *Denticulopsis hustedti*, *Denticulopsis* sp, *Denticulopsis maccolummii*). To test for a local source of terrigenous material deposited at Site 696 we also analysed bedrock samples from Coronation and Powell Island (Fig. 3).

3. Methods and approach

For this study, we investigated the mineralogical and geochemical composition of grains in the sand fraction 0.063–2.0 mm. Mounts of washed sand grains were screened to determine bulk compositions by automated energy-dispersive X-ray spectroscopy on a QEMSCAN® platform which allows micron-scale mapping and mineral identification of samples (Pirrie and Rollinson, 2011). These analyses showed quartz-feldspar sands rich in heavy minerals. To define the sources of the sand grains we performed single