Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Widespread Antarctic glaciation during the Late Eocene

Andrew Carter [a,*], Teal R. Riley [b], Claus-Dieter Hillenbrand [b], Martin Rittner [c]

[a] Department of Earth and Planetary Sciences, Birkbeck, University of London, Malet Street, London WC1E 7HX, UK
[b] British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK
[c] Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK

ARTICLE INFO

Article history:
Received 29 June 2016
Received in revised form 21 October 2016
Accepted 23 October 2016
Available online xxxx
Editor: H. Stoll

Keywords:
Eocene–Oligocene transition
Antarctica
glaciation
IRD
provenance

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 micro-texture data in more proximal records along the Antarctic mar-

* Corresponding author.
E-mail address: a.carter@ucl.ac.uk (A. Carter).

http://dx.doi.org/10.1016/j.epsl.2016.10.045
0012-821X/

Please cite this article in press as: Carter, A., et al. Widespread Antarctic glaciation during the Late Eocene. Earth Planet. Sci. Lett. (2016), http://dx.doi.org/10.1016/j.epsl.2016.10.045

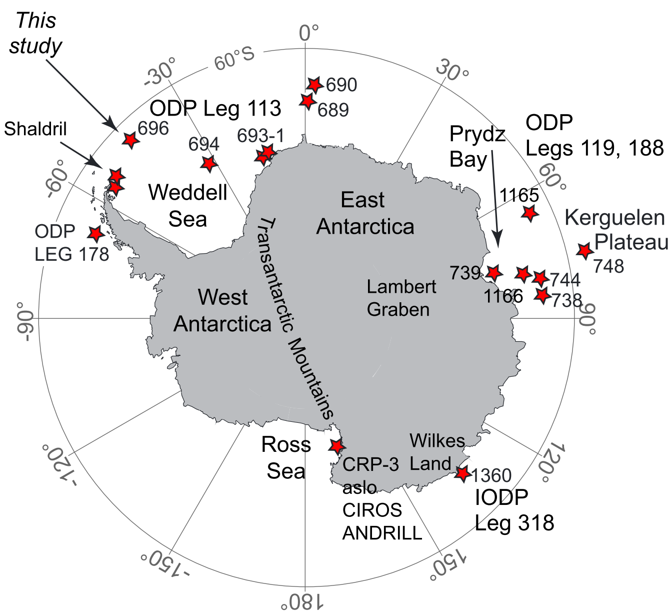

Fig. 1. Present-day locations of areas, where major studies on marine sediments have been undertaken for reconstructing Antarctic ice-sheet history during the Palaeogene and/or Neogene.

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

Please cite this article in press as: Carter, A., et al. Widespread Antarctic glaciation during the Late Eocene. Earth Planet. Sci. Lett. (2016), http://dx.doi.org/10.1016/j.epsl.2016.10.045

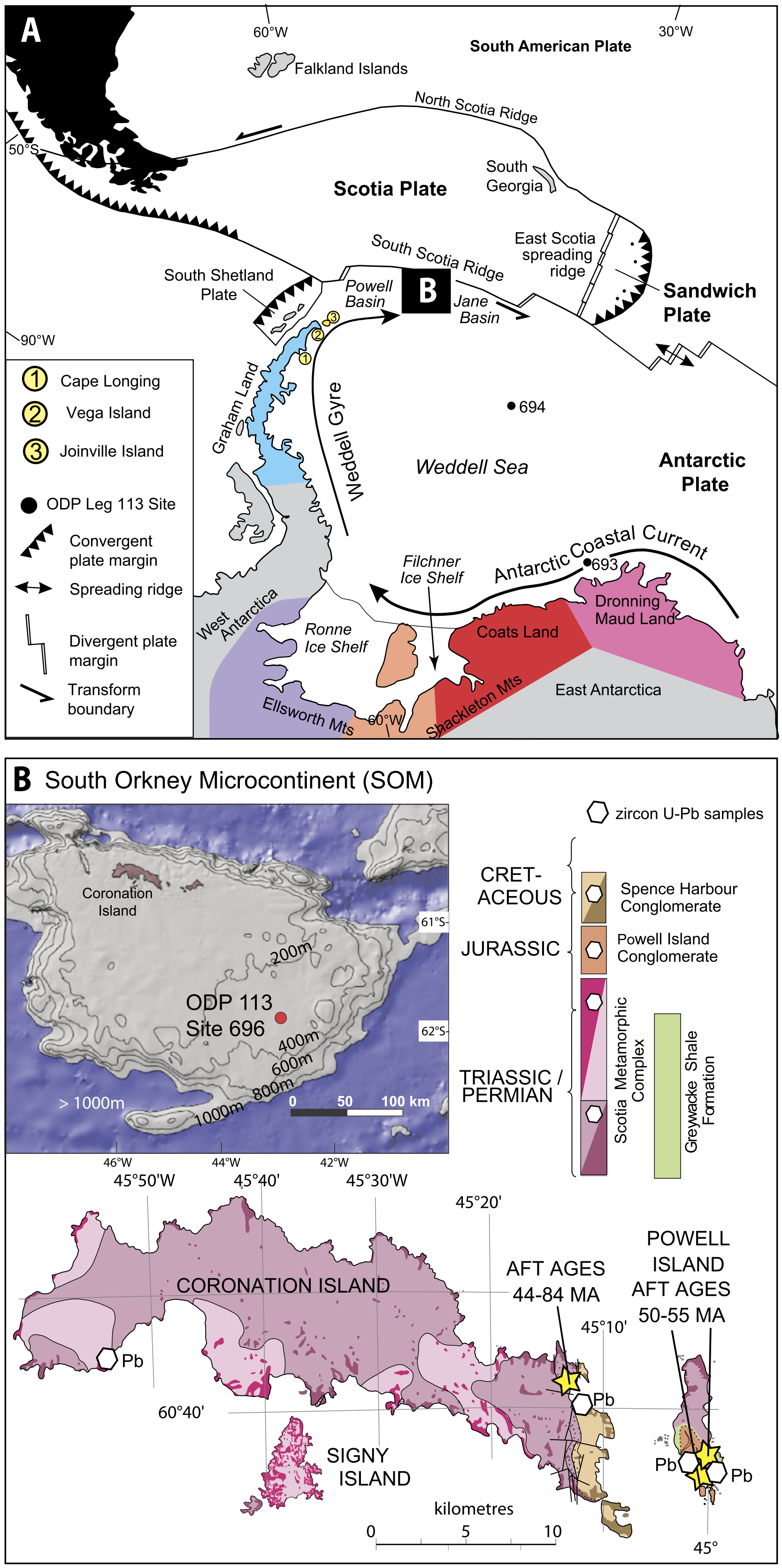

Fig. 2. A) Geography of the Weddell Sea sector and the provenance locations (coloured) referred to in the text. B) Bathymetry of the South Orkney microcontinental shelf, location of Site 696 geology and of Coronation Island and Powell Island and sample sites after Flowerdew et al. (2011).

grain geochronological (zircon U–Pb) and thermochronological (apatite fission track) dating. Populations of single grain ages are used to fingerprint and identify the sand sources by comparing the results to corresponding data previously published from around the Weddell Sea embayment as well as with the new data from the South Orkney Islands and the northern Antarctic Peninsula. This

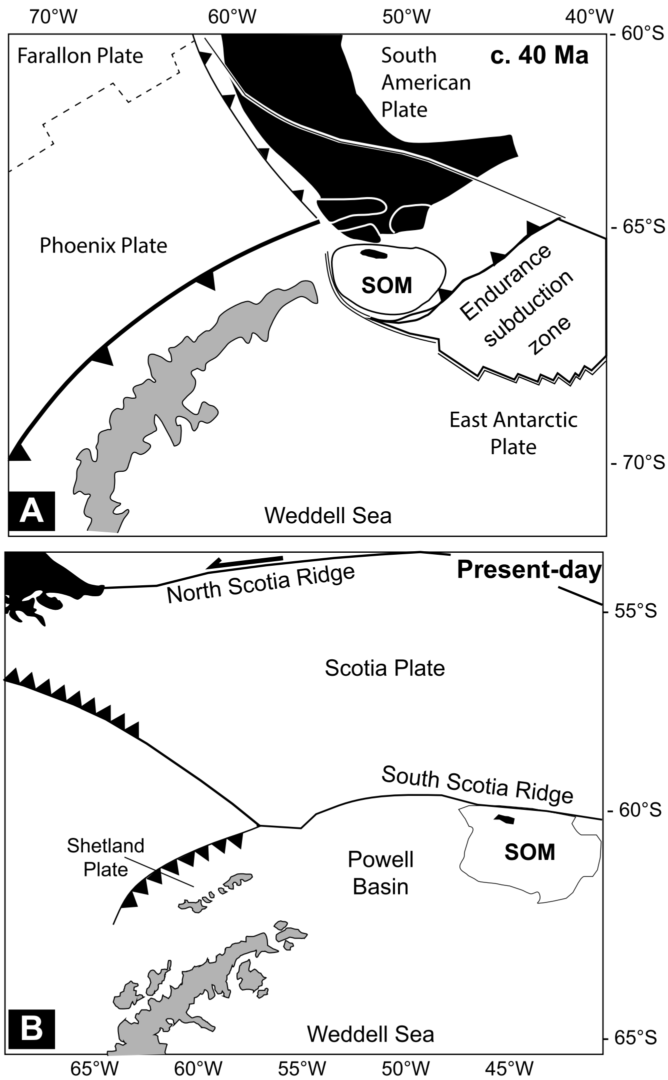

Fig. 3. Paleogeographic reconstruction adapted from Eagles and Jokat (2014) showing (A) the position of the South Orkney Microcontinent during the Middle to Late Eocene. Paleolatitude is from van Hinderbergen et al. (2015). (B) For comparison the present day location is also shown.

approach has been successfully tested in Antarctica where such ages reliably record the geological composition of source areas (Pierce et al., 2014).

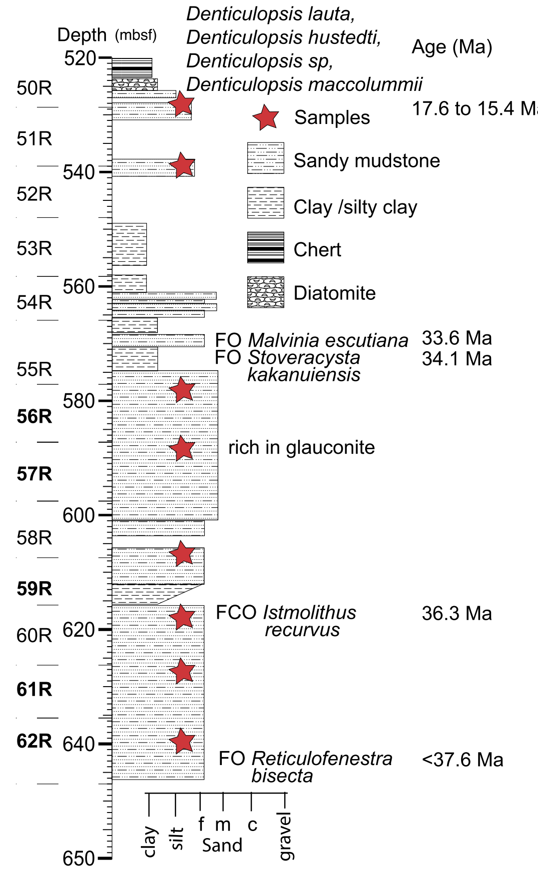

Fig. 4. Stratigraphy and age control for samples from ODP 113 Site 696B.

The sand grains may have come directly from melting icebergs that have calved from ice streams and outlet glaciers into the sea. Sediments deposited at Site 696 contain evidence of coarse-grained (up to 3 cm size) ice-rafted detritus and dropstones in the cores down to a depth of 570 m.b.s.f. (i.e. core 54R which is poorly dated as Late Oligocene to early Miocene). To test whether the finer grained older sediments at Site 696 also contain IRD, we examined microfeatures of quartz grains in the sand fraction 0.1–0.5 mm. High pressure glacial fracturing and abrasion produces grains with high degrees of angularity and relief along with diagnostic microfeatures such as gouges, conchoidal fractures and steps (Mahaney et al., 1996). Although IBRD-derived ice would be expected to be the main source of clastic material delivered to dis-

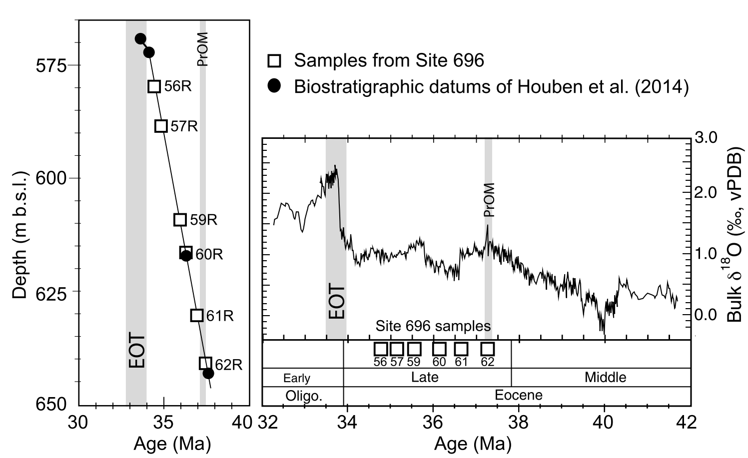

Fig. 5. Age depth plot for Site 696 and the position of the studied samples relative to age and an oxygen isotope record for the Southern Ocean from the middle Eocene to early Oligocene (Scher et al., 2014). EOT = Eocene–Oligocene transition. PrOM = Priabonian oxygen isotope maximum.

Table 1
Summary of grains scanned for composition. Grain outline is based on Powers (1953) classification.

Core	62R	61R	60R	59R	57R	56R	52R	51R
Section	03W	03W	01W	02W	01W	01W	01W	02W
Depth	637.95–645.6	626.2–635.9	616.96–616.6	606.9–616.6	587.6–597.2	577.9–587.6	539.4–548.9	529.8–539.4
Interval (cm)	71–76	69–84		30–45	25–40	129–144	19–28	50–65
Total grains analysed	29,086	14,302	16,496	35,179	53,371	33,987	38,447	54,976
Qtz grains	9,934	15,181	12,741	6,355	3,451	8,731	8,195	7,445
% Qtz in sample	29.2%	28.4	36.2	38.5	24.5	25.7	21.3	13.5
% Plagioclase	22.6	21.5	23.8	23.6	12.8	17.4	44.2	58.4
% Alkali Feldspars	7.2	8.6	12.4	8.2	7.0	7.3	0.9	0.8
% Glauconite grains	6.0	9.4	2.0	0.02	39.3	16.2	2.0	108
% Smectite	6.4	5.8	3.3	0.9	1.1	1.4	4.5	2.9
% Chlorite-illite	2.8	3.5	3.6	1.2	2.4	2.1	0.5	0.7
Qtz grain shape								
% Angular outline	75	75	84	55	63	58	37	64
% Rounded outline	10	7	3	19	22	6	9	10

tal marine locations such as the northern Weddell Sea, there may also be a contribution from sea ice (sea-ice-rafted debris or SIRD). Quartz grains carried by sea ice have rounded edges low relief and chemical features associated with silica dissolution and reprecipitation due to greater levels of chemical weathering (Dunhill, 1998; St John et al., 2015). From each sample, 20–30 quartz grains were randomly selected for analysis of surface microtextures under a Scanning Electron Microscope, and the presence or absence of key features was recorded (Dunhill, 1998; St John et al., 2015). Further methodological details are provided in the supplementary material.

4. Results and interpretation

The investigated samples have grain sizes comprising silt and coarse sand, with the modal grain size being fine sand. Qemscan analysis counted between 14,000 and 55,000 mineral grains in each sample (Table 1) of which 60–72% of the grains were quartz and feldspar. The only exception is a sample from core 57R, which is rich in glauconite. The high (20–59%) feldspar contents in all samples indicate immature, mechanically produced sediments. The abundance of feldspar fluctuates across the stratigraphic age range and is generally mirrored by amounts of smectite and, to a lesser extent illite–chlorite. Chlorite and illite are both influenced by strong physical and weak chemical weathering. Smectite is generally linked to weathering of feldspars so some correspondence is to be expected. Detailed geochemical and clay mineralogical investigations on the Eocene sediments at Site 696 by Robert and Maillot (1990) have previously shown that most of the sediments are of detrital origin and that their smectites resemble those typically found in soils formed in (sub-)tropical regions and/or on parent-rocks of basaltic origin. Some of the smectites revealed features characteristic for an early diagenetic origin, but these were interpreted to have formed during *in situ* recrystallization of smectite within the interstitial sedimentary environment and without any significant chemical or mineralogical change (Robert and Maillot, 1990). The ubiquity (39% of grains) of glauconite in core 57R, and to a lesser extent (16%) in 56R, supports a shallow-water environment enriched in Fe and K. Quartz and feldspar grain shapes are mainly angular.

Quartz grain microfeatures from the oldest samples from cores 62R–59R of Site 696 display high relief, angular mechanical features consistent with IBRD, seen clearly by SEM imaging (Fig. S1A). We also detected some grains with rounded low relief features consistent with SIRD features (Figs. S1B and S1C) but since some grains within each sample have microfeatures of both IRD types we regard the estimated proportions of SIRD or IBRD as indicative only. It is clear though that grains with IBRD features form the largest population and account for 37–84% of all quartz grains based on abundances of high relief angular grains that show breakage blocks, conchoidal and step-like fractures, gouges and striations (Table S2). Some of these grains show edge abrasions, which may result from glaciomarine current reworking or from transport in the glacial environment (Strand et al., 2003), with current-reworked grains being subrounded to subangular, of medium relief and having dissolution features. The remaining grains show features consistent with SIRD (sub angular to well rounded, low to medium relief, high abundance of breakage blocks and microlayering, widespread dissolution features). Some of these grains are fluvial in origin and could be derived from erosion of exposed parts of the SOM or by longer distance IRD transport from the coastal shelf areas bordering the Weddell Sea.

The presence of abundant quartz, feldspar and mica at Site 696 is consistent with continental margin sources and so the simplest explanation is that during the early rifting stages of the Powell Basin at c. 40–30 Ma (Eagles and Jokat, 2014) the SOM was still proximal enough to the Antarctic Peninsula to receive some of its detritus (Barker et al., 1988), and/or the sediment came from exposed parts of the SOM. Comparison of heavy mineral assemblages from this study with modern marine sediment samples in the Weddell Sea region (Diekmann and Kuhn, 1999) points to sources within East Antarctica (Fig. S2). Garnet is widespread in SOM rocks but is rare ($<0.5\%$) in the Site 696 samples (Table S5). This difference is also indicated by the fission track and zircon U–Pb data from South Orkney bedrock.

Apatite fission track (AFT) analyses of bedrock samples from South Orkney (Table S3) gave reset central ages between 33 Ma (H.1181.1: biotite schist of the Permian–Triassic Scotia metamorphic complex) and 56 Ma (H.2113.2: Jurassic Powell Island Conglomerate). The latter sample shows overdispersion of grain ages with a sub-population at 44 ± 3 Ma and a smaller group at 82 ± 1 Ma. Although none of the data yielded sufficient track lengths for thermal history modelling the youngest ages indicate onset of cooling from c. 50–30 Ma, which overlaps with the onset of rifting and extension during early opening of Powell Basin (Eagles and Jokat, 2014). The bedrock AFT data limit the depth of post 30 Ma denudation to <1.5–2 km since any larger denudation would normally have produced younger AFT ages unless the exhumation was extremely rapid. By contrast, the detrital AFT ages from Site 696 are different; core sample 61R revealed a minor population of volcanic apatites with an age of 34 ± 4 Ma and abundant older grains with mean ages between 140 ± 11 and 292 ± 13 Ma. Similar age modes were found in samples 56R and 57R (Fig. S3; Table 2).

The Mesozoic detrital FT ages record the tectono-thermal histories of the apatite source rocks, which are known to vary in the circum Weddell Sea region. To recover these histories the FT age and track length data for each age component were modelled to help locate where the apatites originally came from. Thermal

Table 2
Summary of detrital apatite fission track age modes at Site 696. Accompanying radial plots can be found in the supplementary data.

Sample	No grains	AFT Age group (Ma)	% of grains
61R	60	34 ± 4	45%
		140 ± 11	21%
		292 ± 13	34%
59R	65	89 ± 10	12%
		210 ± 10	75%
		445 ± 66	13%
57R	60	137 ± 6	32%
		291 ± 11	68%
56R	52	120 ± 11	25%
		262 ± 11	75%

history modelling of the oldest apatite fission track age component (Fig. S4) show the ages were produced by a Carboniferous cooling event. This rules out the Antarctic Peninsula as a source since the oldest rapid AFT cooling event from this region dates to the Late Cretaceous and Early Cenozoic (Barbeau, 2011; Guenthner et al., 2010). The only known Late Carboniferous event is in Dronning Maud Land of East Antarctica (Jacobs and Lister, 1999; Meier, 1999; Emmel et al., 2007). The younger FT age mode in the Site 696 samples relates to an early Cretaceous cooling event which has been recorded from Antarctic basement rocks surrounding the Weddell Sea, extending from the Ellsworth Mountains (Fitzgerald and Stump, 1991, 1992) to the Shakleton Ranges and coastal areas of Dronning Maud Land (Emmel et al., 2007; Meier, 1999) (Fig. 2).

Detrital zircon U–Pb data also show similar differences. All Late Eocene samples from Site 696 gave nearly identical age spectra (Fig. 6). The range of age peaks is dissimilar to data from bedrock of the South Orkney Islands and Graham Land on the Antarctic Peninsula, most strikingly by the absence of zircons from the Permian arc (270 Ma peak), which are ubiquitous amongst the rocks of South Orkney and sedimentary successions of northern and eastern Graham Land (Barbeau, 2011). The U–Pb ages of the zircons in the Site 696 samples also reveal Early Cretaceous age peaks and a significant component of grains between c. 1.0–12 Ga that are essentially absent in rocks from northern Graham Land and rare on South Orkney.

To test rigorously the relationship between likely source areas multidimensional scaling (MDS) (Vermeesch, 2013) was applied to the zircon U–Pb results and data from areas bordering the entire Weddell Sea region (Fig. 6), including the shelf of Dronning Maud Land, Coats Land, the East Antarctic drainage basin of the modern Filchner Ice Shelf, the Ellsworth Whitmore Mountains, the Antarctic Peninsula, the South Orkney Islands as well as the Magellanes Basin and the Fuegian Andes, because the SOM was located closer to South America prior to its separation from Antarctica during the Eocene (Eagles and Jokat, 2014) (Fig. 3). The MDS map clearly shows a strong dissimilarity between Site 696 samples and South America, the Antarctic Peninsula and South Orkney, but a significant similarity to the Ellsworth Whitmore Mountains, drainage basin of the Filchner Ice Shelf, the shelf regions of Coats Land and Dronning Maud Land. We also compared Site 696 data with Pliocene sediments from ODP Leg 113 Site 694 on the Weddell Sea abyssal plain. The sediments deposited at this location during the Pliocene are entirely hemipelagic in origin (Kennett and Barker, 1990) and, given the westward directions of the Antarctic Coastal Current and the Weddell Gyre, must have been sourced from East Antarctica. We also analysed one middle Oligocene sample (core 14) from Site 693B on the continental margin of the Weddell Sea, proximal to Coats Land and Dronning Maud Land. In both cases the zircon ages are similar to the Late Eocene zircon dates from Site 696 (Fig. 6).

5. Discussion

The detrital zircon U-Pb and apatite thermochronometry data show that the bulk of the Late Eocene (∼36.5–33.6 Ma) sediments deposited at ODP Leg 113 Site 696 do not originate from local sources (Antarctic Peninsula and South Orkney) but instead were supplied from distal sources. This finding together with the common occurrence of quartz grains with mechanically induced microtextures, which are diagnostic of subglacial erosion and transport, suggests that most of the detritus was supplied by ice-rafting. The provenance of these sand grains best matches sources within the Ellsworth–Whitmore Mountains of West Antarctica and the Weddell Sea coastal region of East Antarctica (Fig. 2). However the significance of these results and implications for understanding the development of the early stages of the Antarctic cryosphere depends on whether they were deposited by directly by melting icebergs, sea ice or were re-deposited by other processes, such as gravity or current flows.

Opening of the Weddell Sea and formation of new oceanic lithosphere initiated in the south at around 147 Ma (Konig and Jokat, 2006) and the main depocentre has remained there to the present-day (Huang et al., 2014). Given that continental-scale river systems drained the Antarctic interior well into the Eocene (Strand et al., 2003) and delivered sediment through the Filchner-Ronne rift basin to this depocentre (Jamieson et al., 2014) it is reasonable to consider that sediment deposited on the SOM shelf may have been re-worked and delivered by long-distance gravity flows that originated along the southern Weddell Sea margins. Today, this would require sand to travel over 1200 km, across the abyssal plains before flowing uphill from water depths >4000 m onto the SOM shelf that has a water depth of 650 m. Reconstructions of Weddell Sea paleobathymetry based on the thermal subsidence history of local ocean crust (Huang et al., 2014) show that a similar depth range existed in the Late Eocene, although the SOM shelf was shallower, c. 100 m (with an uncertainly of a similar order), based on benthic foraminifera diagnostic of a neritic, slightly hyposaline inner shelf environment (Wei and Wise, 1990) and the presence of glauconite. More problematic is that during the Paleogene, to the southwest of the SOM, the Endurance subduction zone (Fig. 2) would have trapped any sediment transported by flows from the south.

Given that gravity flows are an unrealistic mode of transport, the Late Eocene sediments deposited at Site 696 must have been transported to the SOM by ice. Although quartz grain microfeatures are mostly consistent with IBRD some 15–45% of the observed grains show microfeatures consistent with sea-ice transport and/or a fluvial reworking. Whether sea-ice of any significance existed at least during the winter months in the late Eocene is unclear although climate modelling studies show it was certainly possible (DeConto et al., 2007). If (seasonal) sea ice was present because the Antarctic shelf was still shallow during the Late Eocene (Wilson et al., 2013) it could have easily picked up and transported beach sediments. Regardless, the key point is that the glacial derived sand grains were transported to the SOM by ice, mainly by melting icebergs, and that all of the ice sources must have originated in the southern Weddell Sea because their provenance (zircon U–Pb and apatite FT ages) does not match the Antarctic Peninsula or South Orkney.

A number of previous studies have indicated the presence of glacial ice prior to the EOT oxygen event, e.g. work on the SHALDRIL cores recovered from the eastern Antarctic Peninsula shelf (Anderson et al., 2011) and on Late Eocene–Oligocene sediments deposited in a glacio-fluvial environment in Prydz Bay

Please cite this article in press as: Carter, A., et al. Widespread Antarctic glaciation during the Late Eocene. Earth Planet. Sci. Lett. (2016), http://dx.doi.org/10.1016/j.epsl.2016.10.045

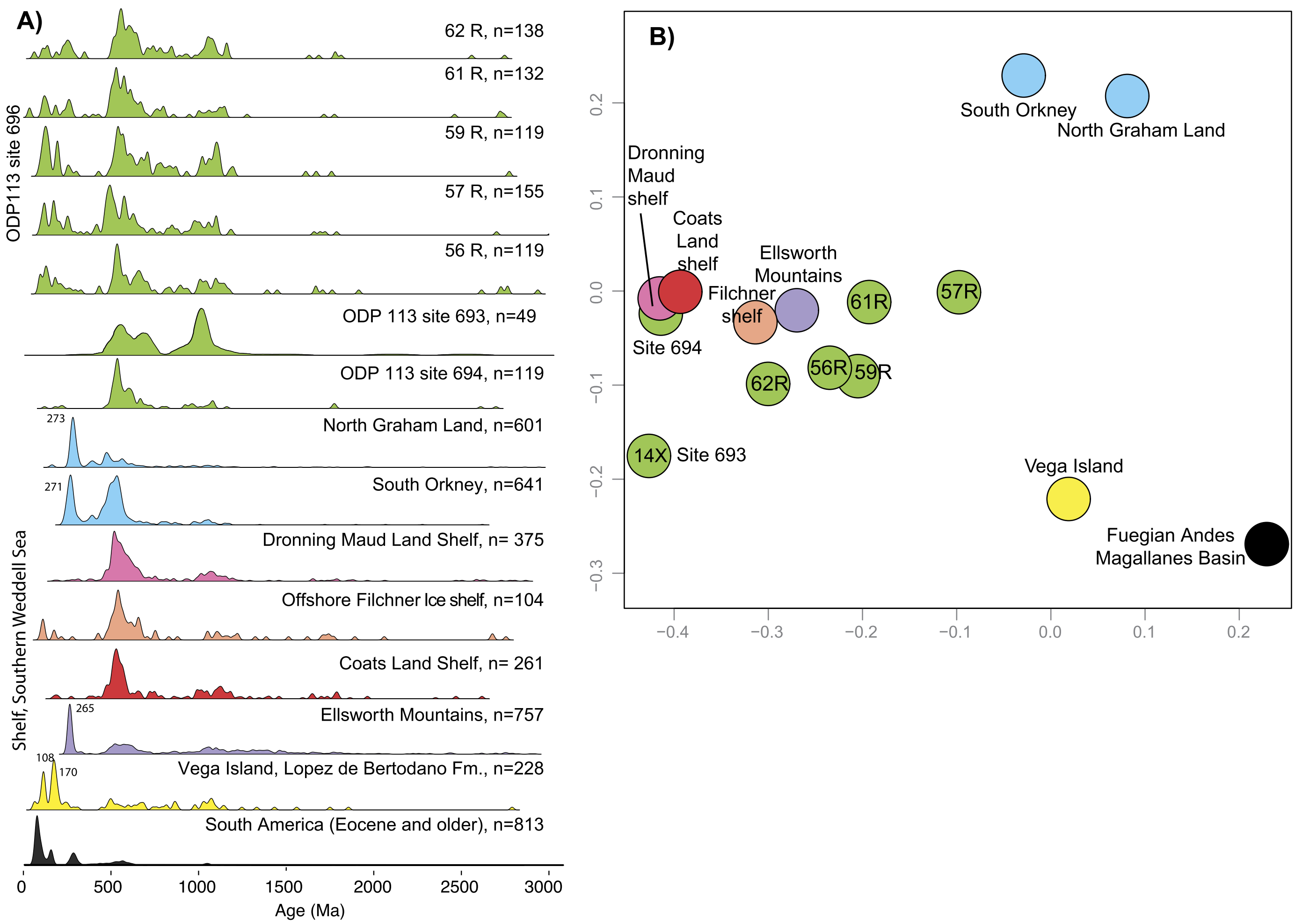

Fig. 6. A). Kernel density plots of detrital zircon ages for samples analysed in this study (South Orkney, Site 696) and compiled datasets for potential source regions (see supplementary data for sources). B). Multidimensional Scaling Maps (Vermeesch, 2013) comparing the age spectra in A. Dissimilar samples (South Orkney, Graham Land, Fuegian Andes, Vega Island) plot far apart. The cluster of similar samples includes Sites 696 and 694, modern sediments from offshore Dronning Maud and Coats Land, the hinterland of the modern Filchner Ice Shelf and bedrock ages from the Ellsworth Mountains (for locations see Fig. 2).

(Barron et al., 1991; Cooper and O'Brien, 2004). Also, the geochemical proxy data from middle-late Eocene sediment deposited on the Kerguelen Plateau found evidence consistent with ephemeral glaciations in East Antarctica (Scher et al., 2014). These studies assumed that the glacial debris came from nearby sources, or was reworked. More direct evidence from the work by Galeotti et al. (2016) on the well-dated CRP-3 drill core at Cape Roberts has revealed evidence of local glacial advance and retreat cycles that date to between 34–31 Ma. Due to the low recovery at Site 696 sample our dataset does not have the temporal resolution to detect orbital scale glacial–interglacial cycles and so cannot demonstrate glacial ice was permanently present throughout the Late Eocene. The recent study by Galeotti et al. (2016), suggested that until 32.8 Ma most of the glacial ice disappeared during peak interglacials. But, significantly, our new data do reveal an older and much wider distribution of glacial ice in Antarctica than any previous work has suggested. There must have been significant ice present across Antarctica in the Late Eocene to enable it to reach low-altitudes and to calve icebergs along the coastlines of the southern Weddell Sea by c. 36.5 Ma or slightly earlier.

The iceberg-rafted grains with both East and West Antarctic provenance provide an unambiguous record for widespread glacial ice around the Weddell Sea embayment between ∼37 and 34 Ma. Whether these areas were the precursors for growth of the EAIS and WAIS is an open question. Most of the Antarctic topography was established before the Late Eocene (Wilson et al., 2012), and the glaciers in the mainly inland mountainous areas in the Gamburtsev Mountains, Dronning Maud Land and the Transantarctic Mountains (Fig. 1) can be expected to have served as the main nuclei for the ice sheets. In simulations of Antarctic ice-sheet growth under high Palaeogene CO_2 concentrations the loci of the largest nuclei are close to the regions that were the sources for most of the IBRD-grains found at Site 696 (DeConto et al., 2007). However, the loci of ice sheet growth in such model simulations can vary considerably under different precipitation, air and ocean temperature, paleolatitude, lapse rate and sea level boundary conditions (cf. van Hinsbergen et al., 2015), all of which have serious uncertainties for the Late Eocene.

Although studies have tended to paint a dominant mechanism as responsible for the onset of glaciation (ocean gateway *vs* CO_2 decline) the relative roles of different mechanisms, and their associated feedbacks are complex and remain poorly resolved because the initial and boundary conditions are still highly uncertain. Despite improvements there remain considerable uncertainties in relation to the atmospheric CO_2 concentrations leading up to the EOT (Anagnostou et al., 2016) as well as the modelled CO_2 threshold for Antarctic glaciation, which are known to be highly model- and model-configuration-dependent (Gasson et al., 2014). Until a more complete continent-wide inventory of early ice on Antarctica can be established and modelling approaches adopt more realistic boundary conditions and a dynamical approach based on an ensemble of mechanisms, the precise role of atmospheric CO_2 concentrations cannot be fully defined.

6. Conclusions

Much emphasis has been placed on climate models to explain the glaciation of Antarctica during the EOT. Sensitivity modelling consistently shows CO_2 decline was sufficient to drive polar cooling but the location and extent of early ice has a dependency on model boundary conditions that are often poorly known and have large uncertainties. Realistic model predictions must be consistent with geological observations and in this context the data from this study are significant as they provide the first evidence for the presence and continuity of widespread ice in the late Eocene that extended from the mountainous interiors to the coastal areas fringing the southern Weddell Sea. We note that paleotemperature reconstructions derived from proxy data (e.g., Douglas et al., 2014) suggest relatively warm conditions in the Weddell Sea and therefore icebergs in the region may not have survived for long. The apparent paradox between the reconstructed temperatures and the results presented in this study, however, can be reconciled, if the full error bars in proxy-based temperature reconstructions for the Late Eocene are taken into account and/or if the westward currents in the Weddell Sea during the Late Eocene were of similar vigour to the present-day. Given that current strength largely depends on local paleogeographic and atmospheric conditions model testing that includes eddy-resolving simulations will need to adopt a finer scale than to date to explore the latter explanation.

Acknowledgements

The research used samples provided by the Ocean Drilling Program (ODP) from Leg 113 Site 696. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. TRR and CDH are supported by the Natural Environment Research Council (NERC). We thank Peter Bijl and two anonymous reviewers for their constructive though critical suggestion.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2016.10.045.

References

Anagnostou, E., John, E.H., Edgar, K.M., Foster, G.L., Ridgwell, A., Inglis, G.N., Pancost, R.D., Lunt, D.J., Pearson, P.N., 2016. Changing atmospheric CO_2 concentration was the primary driver of early Cenozoic climate. Nature 533, 380–384.

Anderson, J.B., Warny, S., Askin, R.A., Wellner, J.S., Bohaty, S.M., Kirshner, A.E., Livsey, D.N., Simms, A.R., Smith, T.R., Ehrmann, W., Lawver, L.A., Barbeau, D., Wise, S.W., Kulhanek, D.K., Weaver, F.M., Majewski, W., 2011. Progressive Cenozoic cooling and the demise of Antarctica's last refugium. PNAS 108, 11356–11360.

Barbeau, D.L., 2011. Exhumation history of the margins of Drake Passage from thermochronology and sediment provenance. In: Anderson, J.B., Wellner, J.S. (Eds.), Tectonic, Climatic, and Cryospheric Evolution of the Antarctic Peninsula. American Geophysical Union, Washington, D.C., p. 63.

Barker, P.F., Kennett, J.P., et al., 1988. Proceedings of the Ocean Drilling Program, Initial Reports, 113. Ocean Drilling Program, College Station, Texas.

Barrett, P.J., 2007. Cenozoic climate and sea level history from glaciomarine strata off the Victoria Land coast, Cape Roberts Project, Antarctica. In: Hambrey, M.J., Christoffersen, P., Glasser, N.F., Hubbard, B. (Eds.), Glacial Sedimentary Processes and Products. In: International Association of Sedimentologists Special Publication, vol. 39, pp. 259–288.

Barron, J., Larsen, B., Baldauf, J.G., 1991. Evidence for Late Eocene to Early Oligocene Antarctic Glaciation and Observations on Late Neogene Glacial History of Antarctica: Results from Leg 119. Proceedings of the Ocean Drilling Program, Scientific Results, vol. 119. Ocean Drilling Program, College Station, Texas, pp. 869–891.

Basak, C., Martin, E.E., 2013. Antarctic weathering and carbonate compensation at the Eocene–Oligocene transition. Nat. Geosci. 6, 121–124.

Bijl, P.K., Pross, J., Warnaar, J., Stickley, C.E., Huber, M., Guerstein, R., Houben, A.J.P., Sluijs, A., Visscher, H., Brinkhuis, H., 2011. Environmental forcings of Paleogene Southern Ocean dinoflagellate biogeography. Paleoceanography 26, PA1202. http://dx.doi.org/10.1029/2009PA001905.

Breza, J.R., Wise Jr., S.W., 1992. Lower Oligocene iceraﬂed debris on the Kerguelen Plateau: evidence for glaciation. In: Wise Jr., S.W., Schlich, R., et al. (Eds.), Proc. ODP Sci. Res., vol. 120, pp. 161–178.

Cooper, A.K., O'Brien, P.E., 2004. Leg 188 synthesis: transitions in the glacial history of the Prydz Bay region, East Antarctica. In: Proceedings of the Ocean Drilling Program, Scientific Results, 188. Ocean Drilling Program, College Station, Texas, pp. 1–42.

Coxall, H., Wilson, P.A., Palike, H., Lear, C.H., Backman, J., 2005. Rapid stepwise onset of Antarctic glaciation and deeper calcite compensation in the Pacific Ocean. Nature 433, 53–57.

DeConto, R., Pollard, D., Harwood, D.D., 2007. Sea ice feedback and Cenozoic evolution of Antarctic climate and ice sheets. Paleoceanography 22, PA3214. http://dx.doi.org/10.1029/2006PA001350.

Diekmann, B., Kuhn, G., 1999. Provenance and dispersal of glacial-marine surface sediments in the Weddell Sea and adjoining areas, Antarctica: ice-rafting versus current transport. Mar. Geol. 158, 209–231.

Douglas, P.M.J., Affek, H.P., Ivany, L.C., Houben, A.J.P., Sijp, W.P., Sluijs, A., Schouten, S., Pagani, M., 2014. Pronounced zonal heterogeneity in Eocene southern high-latitude sea surface temperatures. PNAS 111 (18), 6582–6587. http://dx.doi.org/10.1073/pnas.1321441111.

Dunhill, G., 1998. Comparison of Sea-Ice and Glacial-Ice Rafted Debris Grain Size, Surface Features, and Grain Shape. USGS Open File Rep. 98-367.

Eagles, G., Livermore, R.A., 2002. Opening history of Powell Basin, Antarctic Peninsula. Mar. Geol. 185, 197–207.

Eagles, G., Jokat, W., 2014. Tectonic reconstructions for paleobathymetry in Drake Passage. Tectonophysics 611, 28–50.

Ehrmann, W.U., Mackensen, A., 1992. Sedimentological evidence for the formation of an East Antarctic ice sheet in Eocene/Oligocene time. Palaeogeogr. Palaeoclimatol. Palaeoecol. 93, 85–112.

Emmel, B., Jacobs, J., Crowhurst, P., Daszinnies, M.C., 2007. Combined apatite fission-track and single grain apatite (U–Th)/He ages from basement rocks of central Dronning Maud Land (East Antarctica): possible identification of thermally overprinted crustal segments? Earth Planet. Sci. Lett. 264, 72–88.

Fitzgerald, P.G., Stump, E., 1991. Early Cretaceous uplift in the Ellsworth Mountains of West Antarctica. Science 254, 92–94.

Fitzgerald, P.G., Stump, E., 1992. Early cretaceous uplift of the southern Sentinel range, Ellsworth Mountains, West Antarctica. In: Yoshida, Y., et al. (Eds.), Recent Progress in Antarctic Earth Science. Terra Scientific Publishing Company (TERRAPUB), Tokyo, pp. 331–340.

Flowerdew, M.J., Riley, T.R., Haselwimmer, C.E., 2011. Geological Map of the South Orkney Islands, Antarctica, 1:150 000 scale, 1 edition. BAS GEOMAP2 series, vol. 3.

Galeotti, S., DeConto, R., Naish, T., Stocchi, P., Florindo, F., Pagani, M., Barrett, P., Bohaty, S.M., Lanci, L., Pollard, D., Sandroni, S., Talarico, F.M., Zachos, J.C., 2016. Antarctic Ice Sheet variability across the Eocene–Oligocene boundary climate transition. Science. http://dx.doi.org/10.1126/science.aab0669.

Gasson, E., Lunt, D.J., DeConto, R., Goldner, A., Heinemann, M., Huber, M., LeGrande, A.N., Pollard, D., Sagoo, N., Siddall, M., Wingut, A., Valdes, P.J., 2014. Uncertainties in the modelled CO_2 threshold for Antarctic glaciation. Clim. Past 10, 451–466.

Guenthner, W.R., Barbeau Jr., D.L., Reiners, P.W., Thomson, S.N., 2010. Slab window migration and terrane accretion preserved by low-temperature thermochronology of a magmatic arc, northern Antarctic Peninsula. Geochem. Geophys. Geosyst. 11 (3), Q03001.

Houben, A.J.P., Bijl, P.K., Pross, J., Bohaty, S.M., Passchier, S., Stickley, C.E., Rohl, U., Sugisaki, S., Tauze, L., van de Flierdt, T., Olney, M., Sangiori, F., Sluijs, A., Escutia, C., Brinkhius, H., the Expedition 318 Scientists, 2013. Reorganization of Southern Ocean plankton ecosystem at the onset of Antarctic Glaciation. Science 340, 341–344.

Huang, X., Gohl, K., Jokat, W., 2014. Variability in Cenozoic sedimentation and paleowater depths of the Weddell Sea basin related to pre-glacial and glacial conditions of Antarctica. Glob. Planet. Change 118, 25–41.

Huber, M., Brinkhius, H., Stickley, C.E., Doos, K., Sluijs, A., Warnaar, J., Schellenberg, S.A., Williams, G., 2004. Eocene circulation of the Southern Ocean: was Antarctica kept warm by subtropical waters? Paleoceanography 19, PA4026. http://dx.doi.org/10.1029/2004PA001014.

Jacobs, J., Lister, F., 1999. Post Permian tectono-thermal evolution of western Dronning Maud Land, East Antarctica: an apatite fission-track approach. Antarct. Sci. 11, 457–460.

Jamieson, S.R.R., Stokes, C.R., Ross, N., Rippin, D.M., Bingham, R.G., Wilson, D.S., Marigold, M., Bentley, M.J., 2014. The glacial geomorphology of the Antarctic ice sheet bed. Antarct. Sci. 26, 724–741.

Kennett, J.P., Barker, P.F., 1990. Latest Cretaceous to Cenozoic Climate and Oceanographic Developments in the Weddell Sea, Antarctica: An Ocean-Drilling Perspective. Proceedings of the Ocean Drilling Program, Scientific Results, vol. 113. Ocean Drilling Program, College Station, Texas, pp. 637–960.

Konig, M., Jokat, W., 2006. The Mesozoic breakup of the Weddell Sea. J. Geophys. Res. 111, B12102.

Mahaney, W.C., Claridge, G., Campbell, I.A., 1996. Microtextures on quartz grains in tills from Antarctica. Palaeogeogr. Palaeoclimatol. Palaeoecol. 121 (1–2), 89–103. http://dx.doi.org/10.1016/0031-0182(95)00069-0.

Meier, S., 1999. Paleozoic and Mesozoic tectono-thermal history of central Dronning Maud Land, East Antarctica – evidence from fission-track thermochronology. In: Berichte zur Polarforschung (Reports on Polar Research), p. 337.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., 2005. The Phanerozoic Record of Global Sea Level Change, vol. 310. Science, New York, N.Y., pp. 1293–1298.

Passchier, S., Bohaty, S.M., Jimenez-Espejo, F., Pross, J., Roehl, U., van de Flierdt, T., Escutia, C., Brinkhuis, H., 2013. Early Eocene to middle Miocene cooling and aridification of East Antarctica. Geochem. Geophys. Geosyst. 14, 1399–1410.

Pierce, E.L., Hemming, S.R., Williams, T., van de Flierdt, T., Thomson, S.N., Reiners, P.W., Gehrels, G.E., Brachfeld, S.A., Goldstein, S.L., 2014. A comparison of detrital U–Pb zircon, $^{40}Ar/^{39}Ar$ hornblende, $^{40}Ar/^{39}Ar$ biotite ages in marine sediments off East Antarctica: implications for the geology of subglacial terrains and provenance studies. Earth-Sci. Rev. 138, 156–178.

Pirrie, D., Rollinson, G.K., 2011. Unlocking the applications of automated mineral analysis. Geol. Today 27, 235–244.

Powers, M.C., 1953. A new roundness scale for sedimentary particles. J. Sediment. Petrol. 23 (2), 117–119.

Robert, C., Maillot, H., 1990. Palaeoenvironments in the Weddell Sea area and Antarctic climates, as deduced from clay mineral associations and geochemical data, ODP Leg 113. In: Barker, P.F., Kennett, J.P., et al. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, 113, pp. 51–66.

Scher, H.D., Bohaty, S.M., Smith, B.W., Munn, G.H., 2014. Isotopic interrogation of a suspected late Eocene glaciation. Paleoceanography 29, 628–644. http://dx.doi.org/10.1002/2014PA002648.

St John, K., Passchier, S., Tantillo, B., Darby, D., Kearns, L., 2015. Microfeatures of modern sea-ice-rafted sediment and implications for paleo-sea-ice reconstructions. Ann. Glaciol. 56, 83–93.

Stocchi, P., Escutia, C., Houben, A., Vermeersen, B., Bijl, P., Brinkhuis, H., DeConto, R., Galeotti, S., et al., 2013. Relative sea-level rise around East Antarctica during Oligocene glaciation. Nat. Geosci. 6, 380–384.

Strand, K., Passchier, S., Nasi, J., 2003. Implications of quartz grain microtextures for onset Eocene/Oligocene glaciation in Prydz Bay, ODP Site 1166, Antarctica. Palaeogeogr. Palaeoclimatol. Palaeoecol. 198, 101–111.

van Hinsbergen, D.J.J., de Groot, L.V., van Schaik, S.J., Spakman, W., Bijl, P.K., Sluijs, A., Langereis, C.G., Brinkauis, H., 2015. A paleolatitude calculator for paleoclimate studies. PLoS ONE 10 (6), e0126946. http://dx.doi.org/10.1371/journal.pone.0126946.

Vermeesch, P., 2013. Multi-sample comparison of detrital age distributions. Chem. Geol. 341, 140–146.

Wei, W., Wise, S.W., 1990. Middle Eocene to Pleistocene calcareous nannofossils recovered by Ocean Drilling Program Leg 113 in the Weddell Sea. In: Proceedings of the Ocean Drilling Program, Scientific Results, 113, vol. 188. Ocean Drilling Program, College Station, Texas, pp. 639–666.

Wilson, D.S., Pollard, D., DeConto, R.M., Jamieson, S.S.R., Luyendyk, B.P., 2013. Initiation of the West Antarctic Ice Sheet and estimates of total Antarctic ice volume in the earliest Oligocene. Geophys. Res. Lett. 40, 4305–4309.

Wilson, D.S., Jamieson, S.S.R., Barrett, P.J., Leitchenkov, G., Gohl, K., Larter, R.D., 2012. Antarctic topography at the Eocene–Oligocene boundary. Palaeogeogr. Palaeoclimatol. Palaeoecol. 335–336, 24–34.

Zachos, J.C., Breza, J.R., Wise, S.W., 1992. Earliest Oligocene ice-sheet expansion on East Antarctica: stable isotope and sedimentological data from Kerguelen plateau. Geology 20, 569–573.

Zachos, J.C., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rythyms, and aberrations in global climate 65 Ma to present. Science 292, 686–692.