Earth and Planetary Science Letters 478 (2017) 1–13

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Evidence for a dynamic East Antarctic ice sheet during the mid-Miocene climate transition

Elizabeth L. Pierce [a], Tina van de Flierdt [b], Trevor Williams [c,d,*], Sidney R. Hemming [a,d], Carys P. Cook [e], Sandra Passchier [f]

[a] Department of Earth and Environmental Sciences, Columbia University, New York, NY 10027, USA
[b] Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK
[c] International Ocean Discovery Program, Texas A&M University, College Station, TX 77845, USA
[d] Lamont Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA
[e] Department of Geological Sciences, Imperial College London, London SW7 2AZ, UK
[f] Earth and Environmental Studies, Montclair State University, Montclair, NJ 07043, USA

ARTICLE INFO

Article history:
Received 6 March 2017
Received in revised form 5 August 2017
Accepted 9 August 2017
Available online xxxx
Editor: D. Vance

Keywords:
East Antarctic ice sheet
mid-Miocene climate transition
Wilkes Subglacial Basin
$^{40}Ar/^{39}Ar$ thermochronology
detrital provenance
IODP

ABSTRACT

The East Antarctic ice sheet underwent a major expansion during the Mid-Miocene Climate Transition, around 14 Ma, lowering sea level by ∼60 m. However, direct or indirect evidence of where changes in the ice sheet occurred is limited. Here we present new insights on timing and locations of ice sheet change from two drill sites offshore East Antarctica. IODP Site U1356, Wilkes Land, and ODP Site 1165, Prydz Bay are located adjacent to two major ice drainage areas, the Wilkes Subglacial Basin and the Lambert Graben. Ice-rafted detritus (IRD), including dropstones, was deposited in concentrations far exceeding those known in the rest of the Miocene succession at both sites between 14.1 and 13.8 Ma, indicating that large amounts of IRD-bearing icebergs were calved from independent drainage basins during this relatively short interval. At Site U1356, the IRD was delivered in distinct pulses, suggesting that the overall ice advance was punctuated by short periods of ice retreat in the Wilkes Subglacial Basin. Provenance analysis of the mid-Miocene IRD and fine-grained sediments provides additional insights on the movement of the ice margin and subglacial geology. At Site U1356, the dominant $^{40}Ar/^{39}Ar$ thermochronological age of the ice-rafted hornblende grains is 1400–1550 Ma, differing from the majority of recent IRD in the area, from which we infer an inland source area of this thermochronological age extending along the eastern part of the Adélie Craton, which forms the western side of the Wilkes Subglacial Basin. Neodymium isotopic compositions from the terrigenous fine fraction at Site U1356 imply that the ice margin periodically expanded from high ground well into the Wilkes Subglacial Basin during periods of MMCT ice growth. At Site 1165, MMCT pebble-sized IRD are sourced from both the local Lambert Graben and the distant Aurora Subglacial Basin drainage area. Together, the occurrence and provenance of the IRD and glacially-eroded sediment at these two marine drill sites proximal to the Antarctic continent provide a previously undocumented record of dynamic ice margin change during the 14.1–13.8 Ma interval in three major East Antarctic drainage basins.

1. Introduction

Following the relative warmth of the Miocene Climate Optimum (MCO; 16.8–14.7 million years ago (Ma), Holbourn et al., 2014), Earth's climate cooled, culminating in the Mid-Miocene Climate Transition (MMCT) at ∼14 Ma, which marked a major expansion of the East Antarctic ice sheet (EAIS). During the MMCT in the Southern Ocean, bottom waters cooled by ∼2 °C and sea-surface waters cooled by 6–7 °C (Holbourn et al., 2007; Shevenell et al., 2004, 2008). In the Transantarctic Mountains, vegetation disappeared and mean summer temperatures fell by >8 °C and have not risen significantly above freezing since then (Denton and Sugden, 2005; Lewis et al., 2008). In the Western Ross Sea, the sedimentary record indicates a highly variable Antarctic ice sheet margin during the MCO, including times when the ice margin was retreated beyond the terrestrial margin (Levy, et al., 2016), and ice sheet simulations of this interval suggest that Antarctic ice volume was reduced at times by 30 to 36 m of equivalent sea level, with large areas of the continent free of ice (Gasson et al., 2016). Sea

* Corresponding author.
E-mail address: trevor@ldeo.columbia.edu (T. Williams).

http://dx.doi.org/10.1016/j.epsl.2017.08.011
0012-821X/© 2017 Elsevier B.V. All rights reserved.

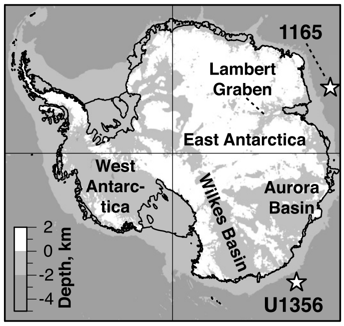

Fig. 1. Location map showing Sites U1356 and 1165 in relation to the major subglacial basins of Antarctica.

level estimates from offshore of NE Australia indicate 59 ± 6 m of sea level fall at ∼13.9 Ma, primarily due to ice growth on Antarctica (John et al., 2011). Overall, over the course of the MMCT, it appears that Antarctic ice grew from a retreated position, potentially restricted to higher altitude glaciation, to a volume similar to that of present day. The drivers of MMCT cooling and associated ice-growth are not fully understood, but have been related to the drawdown of atmospheric CO_2 due to increased carbon burial (e.g., Foster et al., 2012, and references therein), enhanced biological productivity of siliceous organisms in the eastern equatorial Pacific (Holbourn et al., 2014), increased ocean alkalinity (Kender et al., 2014), and/or increased moisture supply to Antarctica (Shevenell et al., 2008).

Antarctic continental paleoenvironmental records that document the MMCT are geographically limited mostly to the Transantarctic Mountains. In marine sediment cores, benthic foraminiferal oxygen isotope records can be used to estimate global ice-volume (e.g. Shevenell et al., 2008) but corrections need to be made for temperature effects, and the locations of ice growth or decay remain unconstrained. Sea level estimates vary by geographic location because of the effects of glacio-isostatic adjustment (e.g. Austermann et al., 2015). Thus, continuously deposited glaciogenic sediment proxy records for Antarctic ice sheet expansion during the MMCT offer an opportunity to improve constraints on this important shift in the global climate system.

Here we present two such records from widely separated marine drill sites offshore of East Antarctica (IODP Site U1356 and ODP Site 1165), which both contain series of layers rich in ice-rafted debris (IRD), including pebble-sized IRD (dropstones), deposited during the MMCT. Both sites contain much lower concentrations of IRD in other parts of the Miocene succession, suggesting an unusually dynamic ice sheet over the course of the transition. Previous marine sediment and IRD provenance studies have delineated source areas with distinct argon and neodymium isotopic compositions that provide a starting point to understand the underlying geology and the nature of ice sheet change in the area of the Wilkes Subglacial Basin, the Aurora Subglacial Basin, and the Lambert Graben (Fig. 1; Pierce et al., 2011, 2014; Cook et al., 2013, 2014, 2017). Building on that foundation, here we present isotope geochemical analyses of individual sand-sized IRD grains and fine-grained sediments at Site U1356, and pebble-sized IRD at Site 1165, to enable us to unravel sediment provenance, source geology, and ice sheet history across the MMCT.

2. Materials and methods

2.1. IODP Site U1356

IODP Site U1356 (136°00′E, 63°19′S, 4003 m water depth) lies 330 km off the Adélie Land Coast of East Antarctica (Fig. 1). Its Miocene sediments consist of diatomaceous ooze interbedded with laminated diatom-rich silty clay, contain intervals of dispersed to common gravel sized clasts, and are interpreted as a period of hemipelagic sedimentation with ice rafting events (Escutia et al., 2011). Clasts larger than 2 mm were counted in the surface of the split core sections, and are most abundant between 171 to 194 m depth (Fig. 2; Escutia et al., 2011). Clast counts were zero or very low outside this interval, but recovery of the middle Miocene sediments averaged 40%, so it is possible that further pulses of IRD were present but were not recovered in the cores.

At Site U1356, we selected 40 samples across the MMCT interval based on lithology and shipboard clast counts (Escutia et al., 2011; Fig. 3) to determine $^{40}Ar/^{39}Ar$ ages of individual ice-rafted hornblende grains, and epsilon neodymium values (ε_{Nd}, defined as the deviation of the measured $^{143}Nd/^{144}Nd$ ratio from the Chondritic Uniform Reservoir value in parts per 10,000) of the terrigenous fine (<63 μm) fraction. In hemipelagic sediments, $^{40}Ar/^{39}Ar$ ages of IRD solely reflect transport by icebergs, whereas fine-grained Nd isotopes reflect a combination of hemipelagic and bottom current transport processes (e.g. Roy et al., 2007; Pierce et al., 2011). Together they provide complementary information on the provenance of glacially derived material.

2.2. ODP Site 1165

ODP Site 1165 (64°27.27′S, 67°13.08′E) is located at 3537.5 m water depth on the continental rise off Prydz Bay, East Antarctica. Samples for this study were taken from the middle Miocene section of Hole 1165B, which had over 80% core recovery. The lithology of the sampled interval consists of structureless greenish gray clay and dispersed sand and gravel (252–305 mbsf) overlying thinly bedded fissile claystones interbedded with up to 1-m thick massive greenish gray claystone beds with dispersed sand grains and rare pebble-sized IRD (305–991 mbsf; O'Brien et al., 2001). The greatest number of clasts larger than 5 mm was found between 280 and 300 mbsf, where the sequence recovery is almost complete (Fig. 2; O'Brien et al., 2001). Clasts are particularly abundant in the lower part of Core 34X (288.5–290.2 mbsf). Laminated sediment occurs both above and below the clast-rich interval of Core 34X (shipboard visual core descriptions, O'Brien et al., 2001), showing that the clasts are stratigraphically in place and do not result from fall-in from the upper part of the hole. There is some core disturbance due to the rotary extended core barrel drilling, and clasts at the very top of each core are likely to be the result of fall-in. For this study, sediments were sieved at 63, 150 μm, and 1 mm revealing a distinctly bi-modal grain size distribution, comprised of mud (<63 μm) and coarse sand and gravel, but virtually no intermediate grain sizes.

About 30 pebbles and cobble sized clasts from the Site 1165 MMCT intervals were disaggregated using a Selfrag electrical pulse fragmentation machine, and any available potassium bearing minerals (hornblende, biotite, muscovite) were analyzed for their $^{40}Ar/^{39}Ar$ thermochronological ages by step heating.

2.3. Age models

The age model for ODP Site U1356 is based on biostratigraphic and paleomagnetic age-tie points published in Tauxe et al. (2012), and listed in Supplementary Table 1. Below 132.15 mbsf we apply linear sedimentation rates between the paleomagnetic age-tie points, and above 132.15 mbsf we apply linear sedimentation rates between the biostratigraphic age-tie points (Fig. 2). Ages for the mid-Miocene recovered at ODP Site 1165 were determined by taking the diatom datums (species and depth) from Florindo et al. (2003), converted to the Average Range Model ages determined by Cody et al. (2008) (Supplementary Table 2). We apply a linear sedimentation rate fit to these points to determine ages for