Insights into the East Antarctic Ice Sheet, 3.5 to 19 Ma, inferred from iceberg provenance

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Summary The past behavior of the Antarctic ice sheets under different climate conditions to today is a topic that bears directly on the stability of the ice sheets under future global warming. While global ice volume history is broadly known from $\delta^{18}O$ in marine sediment records, uncertainties remain, and changes in the geographic extent of the Antarctic ice sheet are not well known. Here we address this deficiency by determining the provenance of Ice-Rafted Debris (IRD) and hence the provenance of the icebergs that carried it, using the isotope geochemical signature of the IRD. ODP Site 1165, 400 km offshore of Prydz Bay, Antarctica, covers the last 20 Ma and is well located to record changes in iceberg provenance over this time. The potential sources of icebergs, Prydz Bay and the coast to the east, have been found to have distinct neodymium and argon isotopic signatures (Roy et al., submitted, van de Flierdt et al., in press). A major provenance change in IRD at Site 1165 is observed between 14 and 7 Ma: before 14 Ma, IRD is locally sourced from the Prydz Bay sector, whereas after 7 Ma, roughly half the IRD comes from the Wilkes Land, Adelie Land, and George V Land. This is likely associated with ice expansion on East Antarctica after the mid-Miocene transition. Additionally, an iceberg drift model has been developed to assess the ocean and climate conditions required to produce the IRD provenance observations. The combination of geochemical provenance analyses and iceberg drift modeling shows promise to be a powerful tool for interpretation of IRD records around Antarctica.

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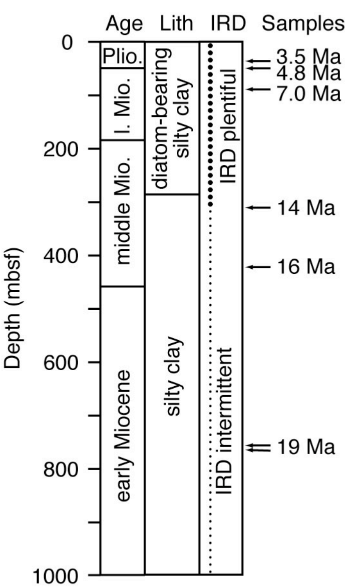

Figure 1. Summary of age, lithology, IRD content of the sediments at Site 1165, with the ages and depths of the samples used in this study.

Introduction

Under some of the global warming scenarios in the 2007 IPCC report, we may face a future where ice cover on Antarctica could not be sustained, and even the relatively stable East Antarctic ice sheet could become unstable. This would not be the first time Antarctica has lost some or all of its ice cover, and to anticipate such changes in the future it is important to understand the history, volume, and geographic extent of past Antarctic glaciation, as well as the interaction of the ice sheet with atmospheric and oceanic circulation patterns.

The broad history of ice on Antarctica is known from the oxygen isotope ratio ($\delta^{18}O$) in foraminifera tests and from ice-rafted debris (IRD) in marine sediments. However, there is only limited geographic understanding of which parts of Antarctica glaciated at what times. Proximal records of ice-sheet extent, while valuable, are often erased by subsequent ice advances. The $\delta^{18}O$ record is affected by both global ice volume and local temperature. Thus there is uncertainty in the ice volume, for example in the early Miocene, Pekar and de Conto (2006) infer that ice reached 50-100% of present volume, while Zachos et al. (2001) classify the Antarctic ice sheet as partial or ephemeral. Hence there is a need for alternative data on past ice extent, of the kind presented here. The provenance data recorded in the isotopic signature of ice-rafted debris provides valuable information on the coastal sectors that are producing icebergs, and on the ocean currents that carry the icebergs.

ODP Site 1165

The aim of this project was to find changes in the source of the IRD at ODP Site 1165, offshore Prydz Bay, over time, and interpret this in terms of the geographic extent of the ice sheet. Site 1165 was drilled during ODP Leg 188 and covers the last 20 Myr in a 999m hole (Figs. 1, 2) (Cooper and O'Brien, 2004). Icebergs from Prydz Bay (Lambert Glacier) drift westward over the site, carried by the polar current, and release their IRD as they melt. For this study, eight samples provide snapshots of ice sheet behavior from 3.5 to 19 Ma (Fig. 1). The time range covers the mid-Miocene transition

(~14 Ma), when, according to $\delta^{18}O$ and sea level records, ice volume increased and it is believed the East Antarctic ice sheet reached its present day extent.

Previously, Williams and Handwerger (2005) had characterized repeated thin IRD-bearing layers in the early Miocene sediments at Site 1165 by IRD counts, opal contents, and downhole log data. The IRD-bearing layers were lithified by silica cement derived from diatoms, and were distinct from the silty clay of the intervening sediment, which contained no IRD. Grützner et al. (2003) studied a late Miocene section (7.0-7.5 Ma) at Site 1165, characterized by alternations between a diatom-bearing hemipelagic facies and a dark grey hemiturbiditic facies. IRD was present throughout, with increased IRD observed in some layers. Both studies inferred that IRD was deposited preferentially during climate warming and glacial retreat, on Milankovitch timescales.

Isotope geochemical source characterization

A combination of Sm-Nd isotopes and $^{40}Ar/^{39}Ar$ ages on the detrital fraction of marine sediments can provide two complementary tracers of sediment provenance. Roy et al. (submitted), van de Flierdt et al. (in press), and Hemming et al. (in press) carried out an isotope geochemical survey on marine core top sediments from all around Antarctica. The results provide a base map for sediment provenance in the Southern Ocean and allow division of Antarctica into seven distinct provenance sectors (Prydz Bay, Dronning Maud Land, Weddell Sea, Peninsula, West Antarctica, Ross Sea, and Wilkes Land).

Argon ages reflect the different tectono-metamorphic events during Antarctica's history. For the Prydz Bay and Dronning Maud Land sectors, $^{40}Ar/^{39}Ar$ ages of 400 to 600 Ma indicate involvement in the Pan-African orogeny ultimately leading to the final assembly of Gondwana (Figs 2, 3) (Roy et al., submitted). Wilkes Land (geographically, ~100°E to 136°E) preserves $^{40}Ar/^{39}Ar$ ages of 1100 to 1300 Ma. Western George V Land and Adelie Land have $^{40}Ar/^{39}Ar$ ages of 1500 to 1700 Ma, and reflect the last major metamorphic event of the Mawson Craton. Similar divisions into geological sectors on land are evident in the zircon U-Pb compilation shown in Figure 2 (Fitzsimons, 2000, 2003).

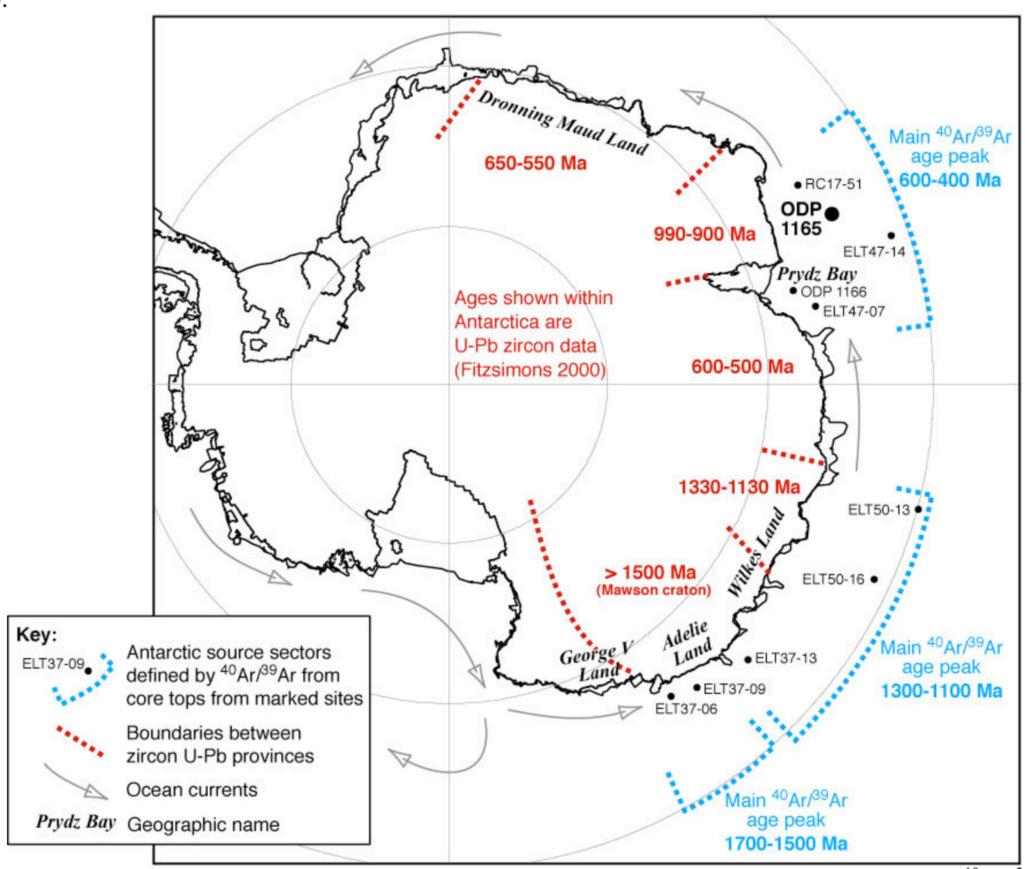

Figure 2. Map showing source areas for IRD provenance studies around East Antarctica. The $^{40}Ar/^{39}Ar$ data are from Roy et al. (submitted) and were measured on hornblende from recent IRD in core tops; the province boundaries are preliminary, pending further analyses from more sites. The zircon U-Pb ages are from a compilation by Fitzsimons, 2000, and represent the youngest U-Pb data from each province; the boundaries are based on samples from both Antarctica and the counterpart areas of Australia and India.

Results

Argon ages for the eight IRD layers investigated at Site 1165 yield an unambiguous result: samples from 14-19 Ma show a predominant Prydz Bay signature, with a main peak in $^{40}Ar/^{39}Ar$ ages around 500 Ma, whereas samples from IRD layers between 3.5 and 7 Ma show a larger spread in Ar ages, with main peaks at 1500-1600 Ma and 1100-1200 Ma in addition to IRD aged 500-600 Ma sourced locally from the Prydz Bay sector (Fig. 3B). This signature is inferred to have been produced by a mixture of IRD from Prydz Bay and the coast to the east, and indicates that for the late Miocene and Pliocene samples about half of the icebergs that melted out over Site 1165 traveled from Wilkes Land and some as far as George V Land.

The IRD peak at 4.8 Ma shows a cluster of $^{40}Ar/^{39}Ar$ ages at 1500-1600 Ma. Comparing to the $^{40}Ar/^{39}Ar$ signature of the potential source areas (Fig. 2, 3A), we can locate the potential source of this IRD to western George V Land and Adelie Land. This IRD may have originated in the Mertz and Ninnis outlet glaciers in this sector. The IRD peaks at 7.0 and 3.5 Ma both show $^{40}Ar/^{39}Ar$ age clusters at 1100-1300 Ma (Fig. 3B), and could be traced to Wilkes Land.

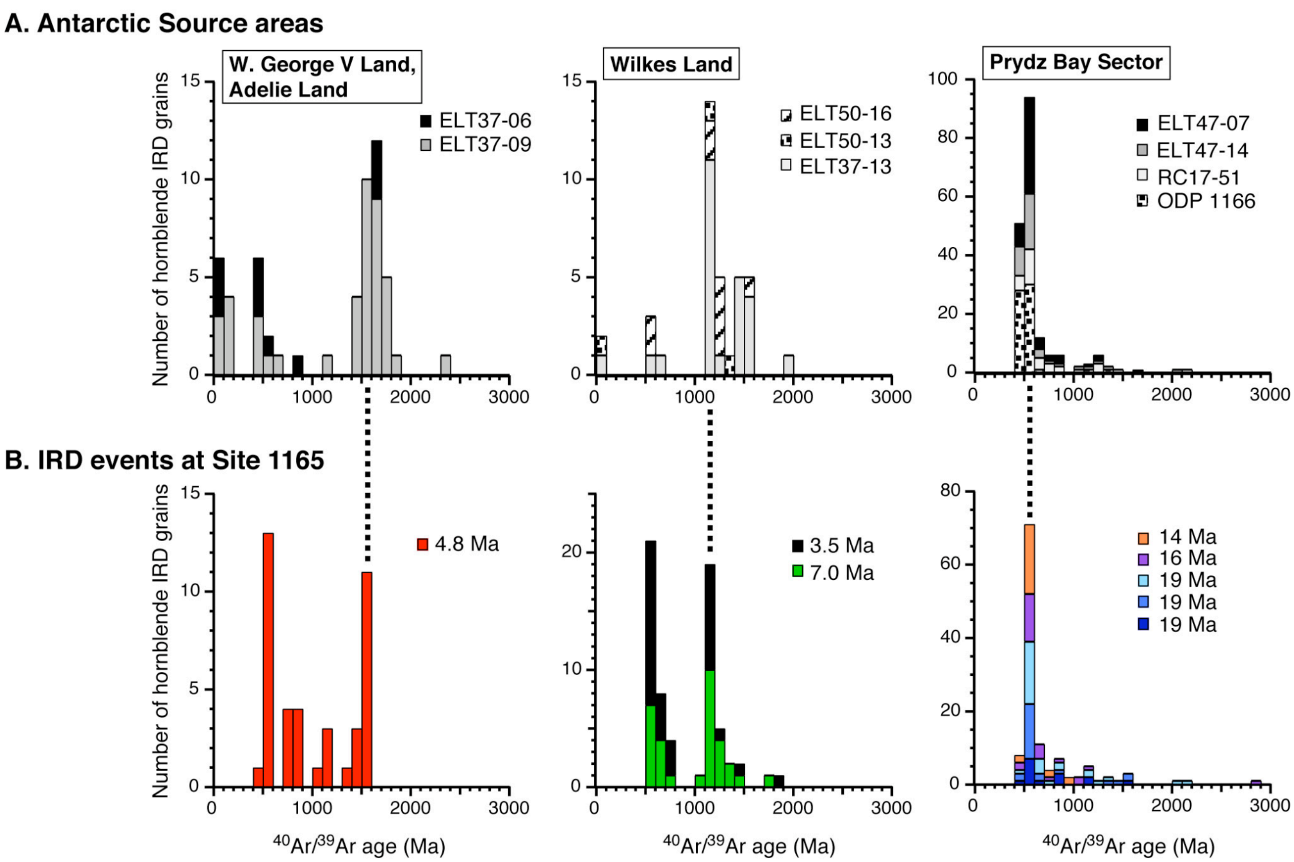

Figure 3. Argon age histograms for: A. three provisional source sectors based on core top $^{40}Ar/^{39}Ar$ data (Roy et al., submitted). B. the samples from the IRD-rich layers at Site 1165 grouped provenance sector. All Site 1165 samples show $^{40}Ar/^{39}Ar$ ages of 500-600 Ma derived locally from the Prydz Bay sector; the 4.8 Ma sample shows a significant contribution of IRD from W. George V Land and Adelie Land; and the 3.5 and 7.0 Ma samples have a significant contribution of IRD from Wilkes Land.

Discussion

Our first hypothesis to explain these results is that ice expanded to the Wilkes Land and George V Land coasts after the mid-Miocene transition, leading to the presence of icebergs from those areas in the 3.5 to 7.0 Ma depositional age samples at Site 1165. The near total absence of Wilkes Land to George V Land icebergs before 14 Ma argues for reduced ice there before this time. However, it is well known that in addition to the presence of coastal ice, a number of other factors, including ocean currents, debris distribution within icebergs, and ocean temperatures contribute to the concentration of IRD accumulated at any one site (Warnke, 1970). A weak westward polar ocean current could also lead to a similar absence of IRD from Wilkes Land and George V Land at Site 1165 before 14 Ma. Indeed, in the core top survey, almost all of the IRD in Prydz Bay is derived locally, when evidently ice is present elsewhere.

To further understand iceberg trajectories, we are combining this IRD provenance study with an iceberg drift model (IDM), that is driven by ice topography, winds and ocean currents. The model was recently developed at McGill University by M. Abrahamowicz and B. Tremblay. Preliminary runs under present day conditions reproduce the motions of real icebergs observed by satellite, and match the finding from the core-top survey. In the model, most of the Wilkes Land icebergs turn north in retroflection zones before reaching Prydz Bay and become entrained in the eastward-flowing circumpolar current. We aim to use the model to predict the distribution of IRD from different source areas under past ice sheet and climatological conditions.

We speculate that both a more extensive ice sheet and stronger westward currents than today would be required to generate and transport icebergs from Wilkes Land and George V Land to Prydz Bay and produce the IRD provenance signal seen in the 3.5 to 7.0 Ma samples at Site 1165.

Conclusions

- The radiogenic isotope composition of proximal circum-Antarctic core tops can be used to decipher the provenance of ice-rafted debris, and hence the source of the icebergs that carried it.
- A major provenance change in IRD is observed between 14 and 7 Ma at ODP Site 1165, offshore of Prydz Bay: before 14 Ma, IRD is locally sourced from the Prydz Bay source sector, whereas after 7 Ma, roughly half the IRD comes from Wilkes Land and further east. We surmise that the provenance change is associated with ice expansion on Wilkes Land and George V Land after the mid-Miocene transition at ~14 Ma. It is also likely that different ocean current conditions from today prevailed in the time snapshots represented by the samples from 3.5 to 7.0 Ma.
- The combination of geochemical provenance analyses and iceberg drift modeling will resolve many of the uncertainties and shows promise of bringing the interpretation of IRD records around Antarctica to a new level.

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References

Cooper, A.K., and P.E. O'Brien (2004), Leg 188 synthesis: transitions in the glacial history of the Prydz Bay region, East Antarctica, from ODP drilling. *In Proc. ODP, Sci. Results, 188* [Online] edited by A.K. Cooper, P.E. O'Brien and C. Richter.

Fitzsimons, I.C.W. (2000), Grenville-age basement provinces in East Antarctica: evidence for three separate collisional orogens. *Geology, 28*, 879-882.

Fitzsimons, I.C.W. (2003), Proterozoic basement provinces of southern and southwestern Australia, and their correlation with Antarctica. *In* Yoshida, M., Windley, B.F., and Dasgupta, S. (eds) 2003. *Proterozoic East Gondwana: Supercontinent Assembly and Breakup.* Geological Society, London, Special Publications 206 93–130.

Grützner, J., M. A. Rebesco, A. K. Cooper, C.F. Forsberg, K. A. Kryc, and G. Wefer (2003), Evidence for orbitally controlled size variations of the East Antarctic ice sheet during the Late Miocene, *Geology, 31*, 777-780.

Hemming, S.R., van de Flierdt, T., Goldstein, S.L., Franzese, A.M., Roy, M., Gastineau, G., and Landrot, G., in press, Strontium isotope tracing of terrigenous sediment dispersal in the Antarctic Circumpolar Current: Implications for Constraining Frontal Positions. (*Geochemistry Geophysics Geosystems*).

Roy, M., van de Flierdt, T. Hemming, S. R., and Goldstein, S. L., submitted, 40Ar/39Ar ages of hornblende grains and bulk Sm/Nd isotopes of Circum-Antarctic glacio-marine sediments: Implications for sediment provenance in the Southern Ocean, *Chemical Geology*

van de Flierdt, T., Goldstein, S. L., Hemming, S. R., Roy, M., Frank, M. and Halliday, A. N., in press, Global neodymium-hafnium isotope systematics revisited, *Earth and Planetary Science Letters*.

Warnke, D. (1970), Glacial erosion, ice-rafting, and glacial-marine sediments: Antarctica and the Southern Ocean, *American Journal of Science*, *269*, 276-294.

Williams, T., and D. Handwerger (2005), A high-resolution record of early Miocene Antarctic glacial history from ODP Site, Prydz Bay, *Paleoceanography*, *20*(PA2017), doi:10.1029/2004PA001067.

Zachos, J. C., M. Pagani, L. Sloan, E. Thomas, K. Billups (2001b), Trends, rhythms, and aberrations in global climate 65 Ma to present, *Science, 292*, 686-693.