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Evidence against a young volcanic origin of the Gamburtsev Subglacial Mountains, Antarctica

Tina van de Flierdt,[1,2] Sidney R. Hemming,[1] Steven L. Goldstein,[1] George E. Gehrels,[3] and Stephen E. Cox[1]

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[1] The Gamburtsev Subglacial Mountains of East Antarctica are among Earth's most enigmatic mountain ranges. They are situated in the middle of Antarctica, buried under hundreds of meters of ice, and reach an elevation of more than 3000 m. These characteristics have given rise to speculation about their origin and composition, in particular whether they are a hotspot or remnants of ancient orogenic events. We studied fluvio-deltaic sands from ODP Site 1166 in Prydz Bay which were deposited prior to the onset of East Antarctic glaciation to address the question of their origin. Results for U-Pb dating of detrital zircons reveal an important age population of ~530 Ma, which is accompanied by a dominant $^{40}Ar/^{39}Ar$ age population of ~519 Ma for detrital hornblendes. The data show no sign of young volcanic contributions, suggesting an old continental origin of the mountains, leaving as enigmatic the cause of their great height and size. **Citation:** van de Flierdt, T., S. R. Hemming, S. L. Goldstein, G. E. Gehrels, and S. E. Cox (2008), Evidence against a young volcanic origin of the Gamburtsev Subglacial Mountains, Antarctica, *Geophys. Res. Lett.*, *35*, L21303, doi:10.1029/2008GL035564.

1. Introduction

[2] The Gamburtsev Subglacial Mountains (hereafter Gamburtsevs) form a major mountain range in the center of Antarctica. Their size is bigger than the European Alps, but their geology is completely unknown, as they are buried under the thick East Antarctic ice sheet. Typically high mountain belts on Earth are associated with active tectonic settings near plate margins (e.g., Andes, Alps, Himalayas). In the case of the Gamburtsevs, the great elevation and dimension are puzzling, considering their location within what we consider to be a stable intraplate setting. Hence, understanding the crustal and upper mantle structure of the Gamburtsev Mountain area is a major target of activities during the ongoing International Polar Year, which includes highly resolved geophysical measurements and drilling through the ice.

[3] One hypothesis concerning the origin of the Gamburtsevs is that they were formed by young hot-spot activity. *Sleep* [2006], for example, notes that they lie on a re-entrant of thin lithosphere within the craton, 150–220 km in thickness, while most of the East Antarctic craton shows lithospheric thicknesses of more than 250 km [*Morelli and Danesi*, 2004]. *Sleep* [2006] suggests that this is the characteristic of lithosphere where Cenozoic magmatism has occurred in Antarctica. An alternative hypothesis is that the Gamburtsevs are an ancient mountain belt [*Veevers and Saeed*, 2008]. This hypothesis is supported by continental scale to regional scale geophysical investigations [*Shapiro and Ritzwoller*, 2004; *Reading*, 2006; *Smith et al.*, 2007]. Recent reconstructions highlight the possibility that the interior of East Antarctica is penetrated by Grenville-age sutures that might have formed during the assembly of the supercontinent Rodinia in Proterozoic times (~1300–900 Ma [*Fitzsimons*, 2003]), and by late Neoproterozoic to Paleozoic mobile belts (~650–500 Ma) marking the assembly of the supercontinent Gondwana (the Pan-African orogeny or Pan-Gondwanaland tectonism [*Veevers*, 2003]). Detailed geophysical studies in the area of Lake Vostok, to the east of the Gamburtsevs, reveal a major crustal boundary in the Antarctic interior, inferred to indicate continental collision during the Proterozoic age [*Studinger et al.*, 2003]. The origin of the Gamburtsevs holds key information for unraveling the position of this part of East Antarctica in supercontinent assembly.

[4] The Gamburtsevs are also of major importance in the context of understanding Cenozoic glaciation on Antarctica. Modeling studies suggest that Antarctic ice may have nucleated at this topographic high during the Eocene [*Huybrechts*, 1993; *DeConto and Pollard*, 2003]. If true, they have played a key role in modulating climate by facilitating major ice growth on Antarctica. If the Gamburtsevs however turn out to be younger than the onset of glaciation, existing models have to be revisited.

2. Sedimentary Provenance as Tool to Understand the Origin of the Gamburtsevs

[5] Here we use the integrated information provided by the geochemistry of terrigenous sediments to understand the history of the Gamburtsevs. Our rationale is that fluvial processes in preglacial times, that is, prior to ~34 Myr [*Zachos et al.*, 2001], should have tapped the Gamburtsev geographic high. Support for this view comes from a reconstruction of the pre-glacial riverine system [*Jamieson and Sugden*, 2007] (Figure 1), suggesting a prominent transport pathway of erosional products from the Gamburtsevs via the Lambert Graben into Prydz Bay. The Lambert Graben is at least as old as Cretaceous [*Stagg*, 1985], and extends about 600 km inland. According to *Jamieson et al.* [2005], such large-scale tectonic features are likely to focus

[1]Lamont-Doherty Earth Observatory and Department of Earth and Environmental Sciences, Columbia University, Palisades, New York, USA.
[2]Now at Department of Earth Sciences and Engineering, Imperial College London, London, UK.
[3]Department of Geosciences, University of Arizona, Tucson, Arizona, USA.

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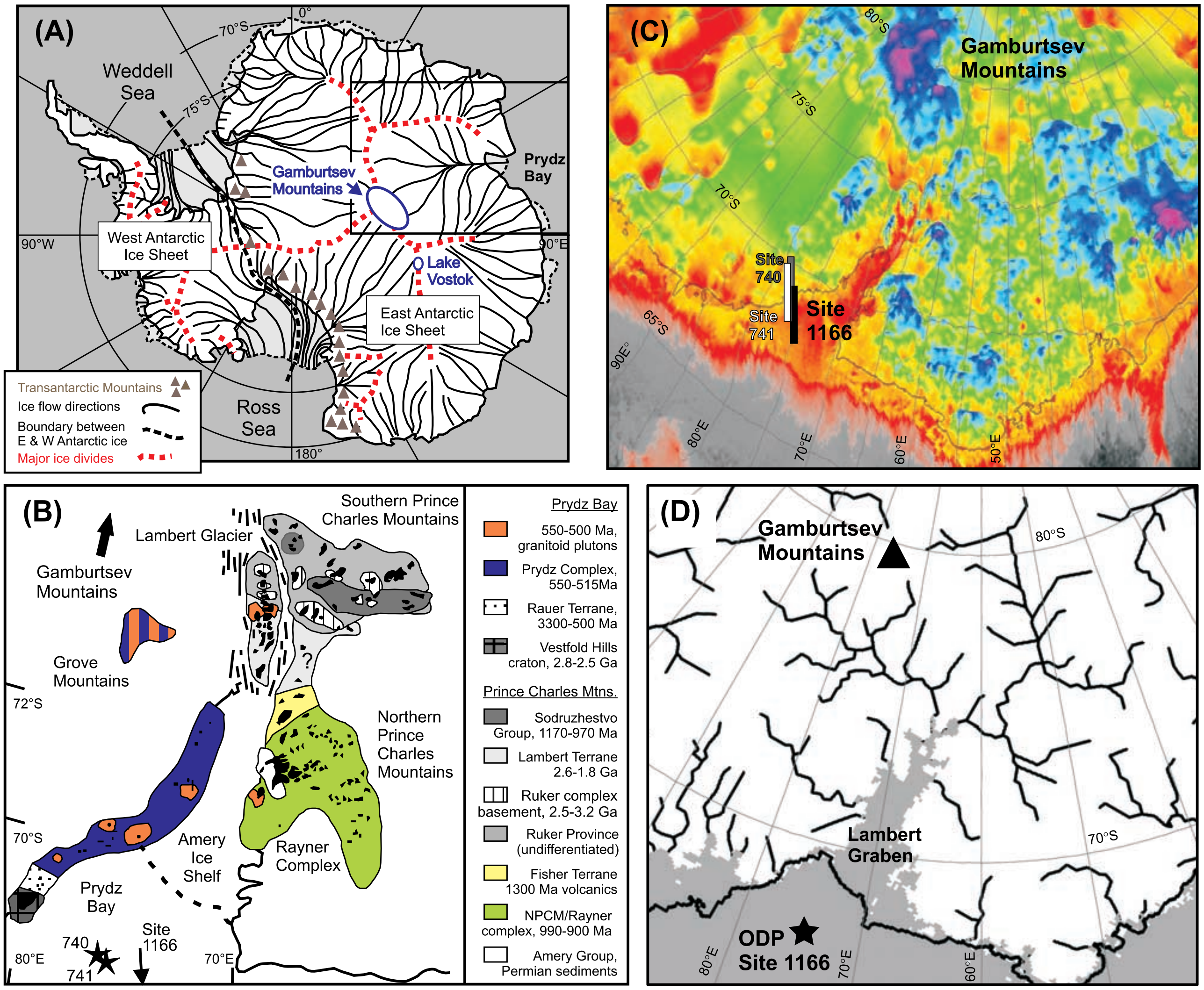

Figure 1. Different maps of Antarctica showing (a) the present day ice drainage pattern [after *Barker et al.*, 2007], (b) the bed elevation beneath the grounded ice sheet in the study area (taken from the BEDMAP Consortium [*Lythe et al.*, 2001]; purple/pink color: >2000 m), (c) the bedrock geology in the study area [after *Fitzsimons*, 2003], and (d) the pre-glacial riverine drainage pattern in the study area [from *Jamieson and Sugden*, 2007].

fluvial systems. We therefore studied ODP Site 1166 (67°41.77′S, 74°47.22′E), from the Prydz Bay continental shelf. Today, this site lies downstream of the Lambert Glacier-Amery Ice Shelf drainage system, the largest single ice stream in Antarctica, draining ~20 % of the East Antarctic Ice Sheet [*Bamber et al.*, 2000] (Figure 1). Site 1166 contains a diverse suite of strata that include pre-glacial, early glacial, and glacial sediments ranging in age from Late Cretaceous to Holocene [*Cooper and O'Brien*, 2004] (Figure 2). Unit III at Site 1166 is composed of massive and deformed sand with silty-clay matrix. SEM analyses of these middle-late Eocene sand grains revealed a high frequency of grains with round edges, indicating deposition on an alluvial plain or delta [*Strand et al.*, 2003]. Nevertheless, 30–50% of the grains in this unit are still angular, indicating glacier sourcing of some of the sedimentary system [*Strand et al.*, 2003]. This is in accordance with the idea that glaciation in Antarctica started with small, ephemeral ice sheets during Eocene times [*DeConto and Pollard*, 2003]. While angular grains may have been supplied from proximal source regions (e.g., shoulders of the Lambert Graben), rounded quartz grains need a certain transport distance to mature, and are likely to reflect the geological hinterland of Prydz Bay. If the Gamburtsevs existed in Eocene times, they would have been by far the most pronounced geographic high, and would therefore have been the prime location for river origin, as indicated by the reconstruction of *Jamieson and Sugden* [2007] (Figure 1).

[6] Our working hypothesis for the remainder of the paper is that if the Gamburtsevs existed in Eocene times, the fluvial sands from Site 1166 are likely to contain at least a small fraction of their erosional products.

3. Samples and Results

[7] We present Sm-Nd isotope analyses on 20 bulk samples from Site 1166, throughout the stratigraphic units (Figure 2 and Data Set S1 of the auxiliary material).[1] The

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/gl/2008gl035564.

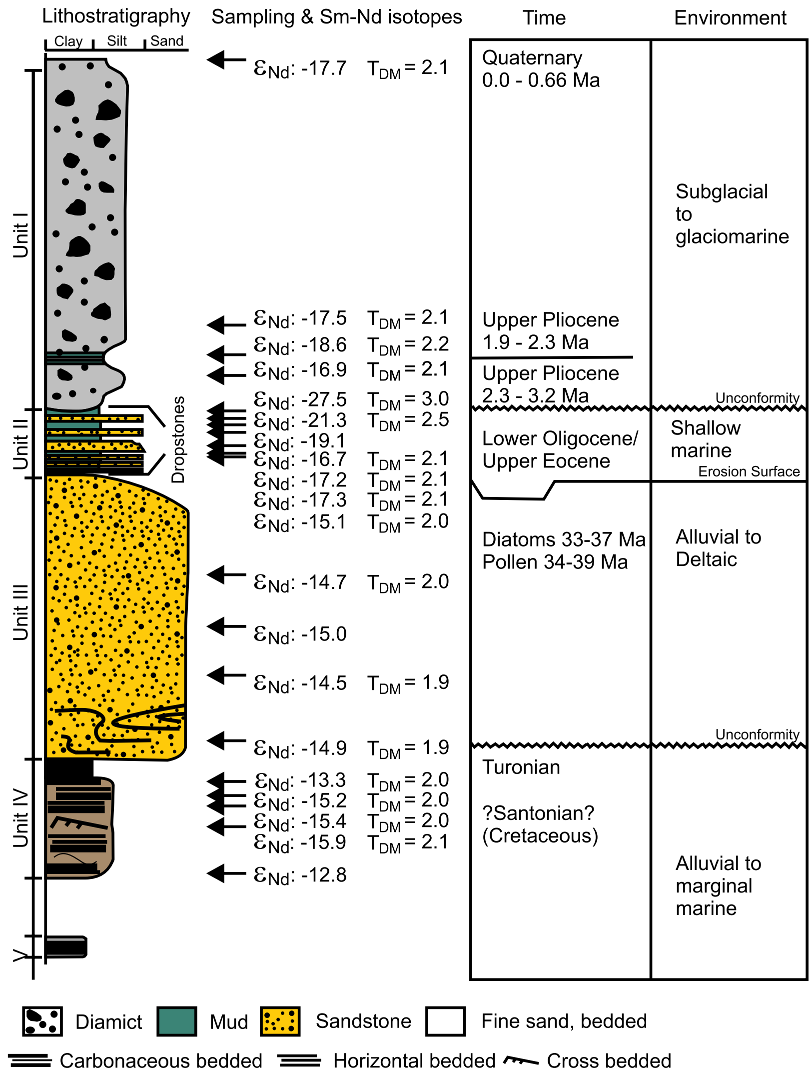

Figure 2. Summary diagram of ODP Site 1166 [from *Cooper and O'Brien*, 2004]. Arrows mark locations of samples used in this study. Numbers are the Nd isotopic compositions of bulk samples (<63 μm) expressed in epsilon units (= deviation of a measured $^{143}Nd/^{144}Nd$ from a bulk earth value in parts per 10,000), and Sm-Nd model ages (crustal residence ages) calculated relative to the depleted mantel (T_{DM}) (Data Set S1).

results (Figure 2) show a uniformly old provenance throughout the sediment column. With the exception of two samples at the top of proglacial Unit II, all samples show Nd isotopic compositions between −12.8 and −19.1, and crustal residence ages between 1.9 and 2.2 Ga.

[8] Three samples were chosen from the fluvio-deltaic Unit III at Site 1166 (1166A 22 1W 60–62 cm, 24 1W 80–82 cm, 26 1W 100–102 cm; Figure 2) and processed for detrital grain geochronology. Isotopic ages date the time at which diffusion of parent-daughter isotopes effectively ceases, which happens at a different temperature for each isotope system and for each mineral (>900°C for U-Pb in zircon; ~400–600°C for $^{40}Ar/^{39}Ar$ in hornblende; ~350–400°C for $^{40}Ar/^{39}Ar$ in biotite, and ~300–350°C for $^{40}Ar/^{39}Ar$ in muscovite [*Reiners et al.*, 2005]). Uranium-Pb age analyses of 232 zircons by laser ablation ICP-MS yield a dominant Pan-African age peak at ~529–546 Ma and a secondary broader peak at ~809–1025 Ma (Figure 3 and Data Set S3), reflecting the crystallization ages of the zircons. $^{40}Ar/^{39}Ar$ ages on 213 hornblende grains from the same three samples show a clear probability peak at 505–512 Ma (Figure 3 and Data Set S2), indicating rapid cooling through ~550°C following Pan-African heating. For one sample (1166A 26 1W 100–102 cm), biotites (n = 16) and muscovites (n = 19) have been separated for $^{40}Ar/^{39}Ar$ analysis. Resulting age probability peaks of 502 and 501 Ma are only slightly younger than the hornblende peak at 517 Ma (n = 112), further supporting the notion of fast cooling after a major orogenic event (Figure 3).

4. Discussion and Implications for the Origin of the Gamburtsevs

[9] The downcore record of Sm-Nd data at Site 1166 can only be explained with a provenance of the sediments from old continental crust. The data are incompatible with any major young volcanic activity in the region as such activity would have left a distinct isotopic fingerprint (e.g., positive

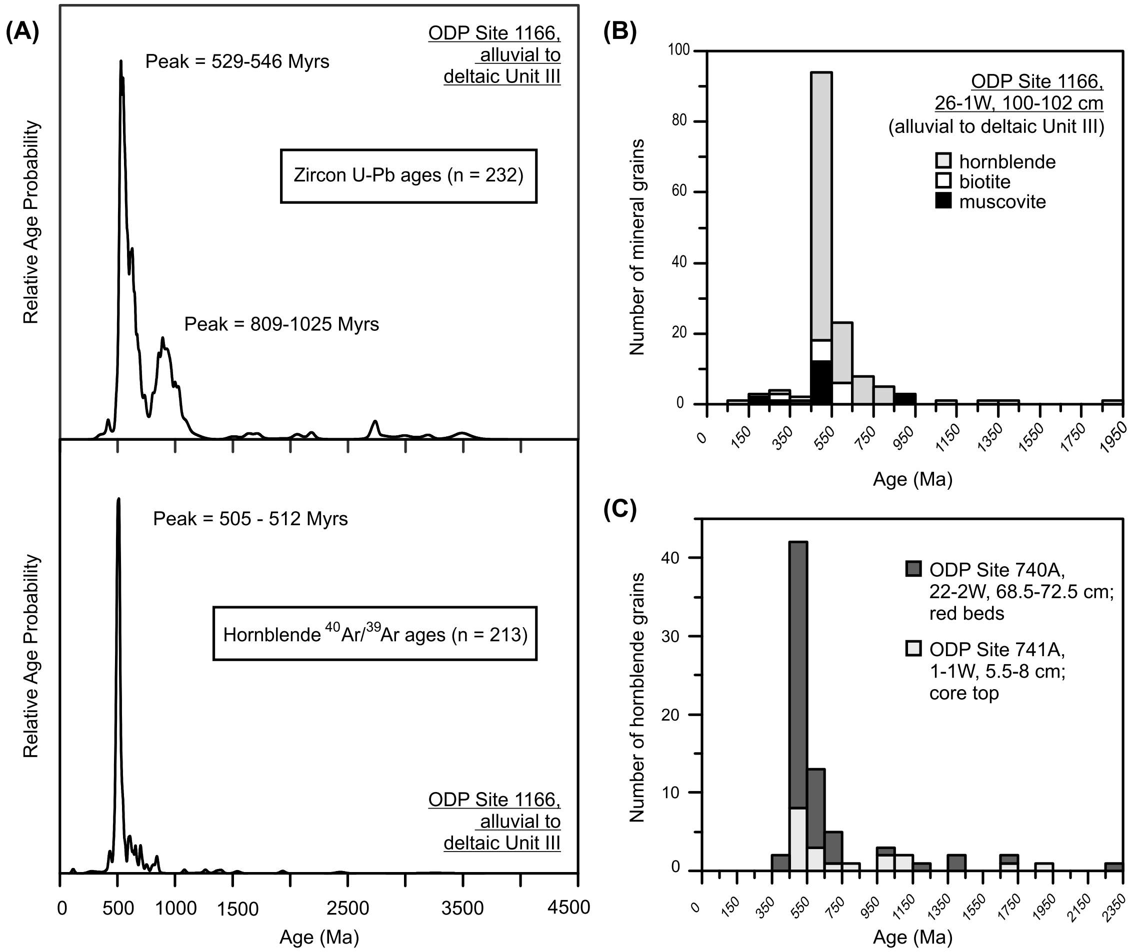

Figure 3. Geochronological results to constrain the age of the Gamburtsevs based on detrital mineral ages from marine sediments in the Prydz Bay area. (a) Stacked probability plot of U-Pb zircon ages for the Eocene alluvial to deltaic sequence at Site 1166 from three distinct samples (ODP Site 1166A 22 1W 60–62 cm, 24 1W 80–82 cm, 26 1W 100–102 cm; Data Set S3), in comparison to stacked probability plots of $^{40}Ar/^{39}Ar$ hornblende ages for the same samples (Data Set S2). The similar ages of the most prominent peaks for zircon U-Pb and hornblende $^{40}Ar/^{39}Ar$ ages suggest a rapid cooling from a major orogenic event at ~530 Ma. (b) The $^{40}Ar/^{39}Ar$ ages of mica and hornblende grains on sample ODP Site 1166A 26 1W 100–102 cm; similar age peaks for minerals with different closure temperatures support rapid cooling after ~530 Ma. (c) Core top sample and Permian(?) red bed layer from DSDP Sites 741 and 740, respectively. Both sites are located in-between Site 1166 and the coastline in Prydz Bay (Figure 1) and confirm that pre-glacial sediments deposited in Prydz Bay had an old provenance [see also *Veevers and Saeed*, 2008].

Nd isotopes). Hence we conclude that a young hot-spot related origin of the Gamburtsev Mountains is highly unlikely. The geochronological data from the fluvial sands at Site 1166 support this notion, and reflect a source region with a tectonothermal age of ~530 million years.

[10] How likely is it now that his age reflects the age of the crust of the Gamburtsevs? East Antarctica is composed of mostly high-grade terranes with Achaean to Neoproterozoic ages [*Tingey*, 1991]. Their relative position to each other was only finalized during the assembly of Gondwana ~650 to 490 Ma [*Veevers*, 2003]. For the Prydz Bay area, a pervasive tectono-metamorphic event with prominent U-Pb zircon ages around ~550–490 Ma is evident in the northern part of the southern Prince Charles Mountains, the Grove Mountains, and along the Prydz Bay coast [*Liu et al.*, 2007] with peak metamorphic conditions at ~535–530 Ma [*Fitzsimons*, 2003] (Figure 1). In contrast, the southern part of the southern Prince Charles Mountains is characterized by Achaean to Proterozoic U-Pb zircon ages [*Phillips et al.*, 2006] and the northern Prince Charles Mountains are dominated by Meso- to Neoproterozoic ages (990–900 Ma; e.g., the Rayner Complex [*Boger et al.*, 2000]).

[11] If the tectonothermal age of ~530 Ma for the fluvial sediments at Site 1166 is derived from the Gamburtsevs, this would suggest that Neoproterozoic to Cambrian tectonism to the east of the Lambert Graben continued inland, maybe even across East Antarctica to connect similar aged rocks in the Transantarctic Mountains with the Prydz Bay area as suggested by *Fitzsimons* [2003]. The paucity of older ages in the $^{40}Ar/^{39}Ar$ spectrum on hornblende grains from Site 1166, as well as from other sites in the Prydz Bay area [*Phillips et al.*, 2007; *Wilson et al.*, 2007], indicating complete resetting of the Ar clock during peak metamorphism and rapid cooling below ~550°C at 510–520 Ma and

below ~300–400°C at ~500 Ma (Figure 3 and Data Set S2), would support such a pervasive tectono-metamophic event across large parts of East Antarctica.

[12] Further support for major late Neoproterozoic to Cambrian tectonism in the ice-covered East Antarctic hinterland comes from Permian-Triassic red beds in the Lambert Graben area. Following the idea of Permian drainage radiating from the Gamburtsev Mountains, Veevers and colleagues [*Veevers and Saeed*, 2008; *Veevers et al.*, 2008] link morainal clasts of red Permian siltstone in the southern Prince Charles Mountains, the Permo-Triassic Amery Group in the northern Prince Charles Mountains, and Permian(?) deposits at ODP Site 740 in Prydz Bay. All these red beds reveal detrital U-Pb zircon age clusters around 620–460 Ma [*Veevers and Saeed*, 2008], supporting a southern extension of Pan-Gondwanaland tectonic activity into the interior of East Antarctica. Independently, we analyzed one sample from the red bed sequence at ODP Site 740 in Prydz Bay for $^{40}Ar/^{39}Ar$ ages in hornblende grains, and two samples from the pre-glacial parts of ODP Sites 740 and 741 each for Sm-Nd isotopes. Argon ages from 56 hornblende grains cluster tightly around a peak age of ~500 Ma, with only a few grains showing older ages. Sm-Nd crustal residence ages of Cretaceous(?) sediments at Site 741 are ~1.9 Ga (Data Set S1), identical to Eocene fluvial deposits from Site 1166, and rock clasts recovered from the Vostok ice core [*Delmonte et al.*, 2004]. However, the crustal residence ages for two Permian(?) red bed samples at Site 740 are 2.4 and 2.5 Ga, older than our other results, but similar to previously presented results from the same site [*Veevers and Saeed*, 2008].

[13] Detrital zircons from Permo-Triassic deposits in the Lambert Graben area also reveal another U-Pb age peak at ~1200 and 800 Ma [*Veevers and Saeed*, 2008], broadly consistent with our secondary age peak (~900–970 Ma) from the Eocene fluvial deposits at Site 1166. They are also broadly consistent with rock clasts from the Vostok ice core (U-Pb zircon age cluster of 0.7–1.2 Ga), suggesting a Meso- to Neoproterozoic age component in the Antarctic basement to the west of Lake Vostok [*Leitchenkov et al.*, 2007]. Such Grenvillian-type ages around Antarctica have been associated with the assembly of the supercontinent Rodinia, and are widespread in the area west of Prydz Bay (i.e., Rayner Complex). The exact locations of mobile belts and tectonism during this time is difficult to reconstruct, due to the later extensive tectonothermal overprint with Pan-African ages of ~650–500 Myr [*Veevers*, 2003], and the lack of rock exposure in the interior of Antarctica. Our new data, add to the existing evidence that the center part of the East Antarctic Shield is made up of a Paleoproterozoic craton that is cut by Grenville- and Pan-Gondwana-age mobile belts.

5. Concluding Remarks

[14] The new geochronological data for ODP Site 1166 provide evidence towards constraining the origin of the enigmatic Gamburtsev Subglacial Mountains, East Antarctica. Downcore Sm-Nd isotopes show no signs of young volcanism in the region, rendering a hot-spot related origin for the mountain belt unlikely.

[15] Geochronological data on fluvio-deltaic deposits of Eocene age yield a crystallization age of ~530 Ma. Assuming that a significant fraction of this material was derived from the Gamburtsev Mountains through pre-glacial riverine drainage, a Pan-African origin can be assigned to the mountains, putting them in causal relationship to Pan-Gondwanaland tectonism and high-grade metamorphism, marking the final assembly of Gondwana. We note however that this interpretation has to remain speculative due to widespread tectonism of this age in eastern Antarctica.

[16] Concerning the uplift history of the Gamburtsev Mountains, we are still missing solid evidence for the timing of uplift. In general, Paleozoic or Precambrian age mountain ranges are not high elevation mountains any more. An explanation could invoke intermittent uplift due to far-field stress during the Variscan collision of Gondwana and Laurasia ~320 Myr [*Veevers*, 1994; *Veevers and Saeed*, 2008]. The best way to tackle this question in the future will be to complement the high-temperature geochronology data presented here with low-temperature chronometers.

[17] **Acknowledgments.** Samples from ODP Sites 1166, 740, and 741 were provided by the Ocean Drilling Program. M. Machlus is gratefully acknowledged for help in and around the Argon lab, and S.S.R. Jamieson and D.E. Sugden for generous supply of figure material and fruitful discussion. This project was made possible through NSF-OPP 0538580 grant to SRH, TvdF, and SLG. This is Lamont contribution 7200.

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S. E. Cox, S. L. Goldstein, and S. R. Hemming, Lamont-Doherty Earth Observatory, Columbia University, 61 Route 9W, Palisades, NY 10964, USA.

G. E. Gehrels, Department of Geosciences, University of Arizona, 1040 E. 4th Street, Tucson, AZ 85721, USA.

T. van de Flierdt, Department of Earth Sciences and Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK. (tina.vandeflierdt@imperial.ac.uk)