Extremely low long-term erosion rates around the Gamburtsev Mountains in interior East Antarctica

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[1] The high elevation and rugged relief (>3 km) of the Gamburtsev Subglacial Mountains (GSM) have long been considered enigmatic. Orogenesis normally occurs near plate boundaries, not cratonic interiors, and large-scale tectonic activity last occurred in East Antarctica during the Pan-African (480–600 Ma). We sampled detrital apatite from Eocene sands in Prydz Bay at the terminus of the Lambert Graben, which drained a large pre-glacial basin including the northern Gamburtsev Mountains. Apatite fission-track and (U-Th)/He cooling ages constrain bedrock erosion rates throughout the catchment. We double-dated apatites to resolve individual cooling histories. Erosion was very slow, averaging 0.01–0.02 km/Myr for >250 Myr, supporting the preservation of high elevation in interior East Antarctica since at least the cessation of Permian rifting. Long-term topographic preservation lends credence to postulated high-elevation mountain ice caps in East Antarctica since at least the Cretaceous and to the idea that cold-based glaciation can preserve tectonically inactive topography. **Citation:** Cox, S. E., S. N. Thomson, P. W. Reiners, S. R. Hemming, and T. van de Flierdt (2010), Extremely low long-term erosion rates around the Gamburtsev Mountains in interior East Antarctica, *Geophys. Res. Lett.*, *37*, L22307, doi:10.1029/2010GL045106.

1. Introduction

[2] The enigmatic GSM and the surrounding basin maintain high topography [*Dalziel*, 1992; *Jamieson and Sugden*, 2008] despite little recent tectonic activity. Preliminary airborne radar results from the Antarctica's Gamburtsev Province Project (AGAP) [*Wolovick et al.*, 2009; *Bo et al.*, 2009] confirm that the GSM comprise tall, jagged peaks with elevations and topographic relief over 3000 m. They are located in the middle of the >500 Ma East Antarctic Craton with no obvious formation mechanism [*Veevers*, 1994; *Sleep*, 2006; *Veevers et al.*, 2008a]. Many assume that they formed recently because conventional wisdom holds that old mountains have moderate elevation and relief.

[3] *Sleep* [2006] proposed that the mountains formed by hot spot magmatism, but this is unlikely because zircon U-Pb ages in Prydz Bay sediments are >500 Ma and there is no significant bulk sediment ϵ_{Nd} shift that would indicate the presence of young bedrock [*van de Flierdt et al.*, 2008; *Veevers et al.*, 2008b]. *Veevers* [1994] proposes mountain formation by the "inversion of a postulated intracratonic superbasin" due to far-field compression during the ~320 Ma formation of Pangaea, which may have been responsible for the reactivation or even creation of elevated topography. *van de Flierdt et al.* [2008] showed that detrital zircon U-Pb and hornblende $^{40}Ar/^{39}Ar$ ages from this region are >500 Ma, suggesting that the last major orogenesis was Pan-African (480–600 Ma).

[4] High-elevation mountain ice caps may have emerged during the late Cretaceous (~100 Ma) or earlier [*Stoll and Schrag*, 1996; *Miller et al.*, 2008], potentially altering regional topographic evolution since as far back as the Permian [*Veevers*, 1994]. If these mountain ice caps were cold-based for a significant portion of this time, erosion rates underneath the ice may have been much lower than during ice-free or warm-based glacial times [*Fabel et al.*, 2002]. Glaciers can efficiently limit elevation, but this "glacial buzzsaw" effect only applies in tectonically active settings under wet-based glaciation [*Thomson et al.*, 2010].

[5] Recent airborne radar results from AGAP suggest that much of the pre-glacial drainage from the Gamburtsev Mountains flowed east toward Wilkes Land, but significant flow features to the north and the extremely low average erosion rates in the Lambert Graben require that fast erosion in the Gamburtsev Mountains would dominate the detrital signal in Prydz Bay if it had occurred for a prolonged period of time. Furthermore, the geometry revealed by AGAP appears to require low erosion rates as long-term fast erosion would have erased extant V-shaped fluvial valleys flowing from the northern flank of the mountains toward the Lambert Graben and overfilled the apparently closed basins between the mountains and Prydz Bay [*Wolovick et al.*, 2009].

[6] Erosion in the Lambert Graben-Prydz Bay Basin can be characterized through the detrital geochemistry of sediments in Prydz Bay. An extensive fluvial network drained a larger catchment area around the Lambert Graben including part of the Gamburtsev Mountains prior to continental glaciation [*Jamieson and Sugden*, 2008]. *Jamieson et al.* [2005] found that the Lambert Graben-Prydz Bay drainage system experienced fluvial erosion since at least rifting from India during Gondwana breakup at 118 Ma. Based on the sediment pile in Prydz Bay, they estimated erosion rates for the last 118 Ma of only 0.001–0.002 km/Myr, an important local constraint that implies that high erosion rates from inland topography would not be overwhelmed by local sources. We measured apatite fission-track and (U-Th)/He cooling ages in order to characterize erosion rates through the thermal history of the dominant sediment sources in the catchment

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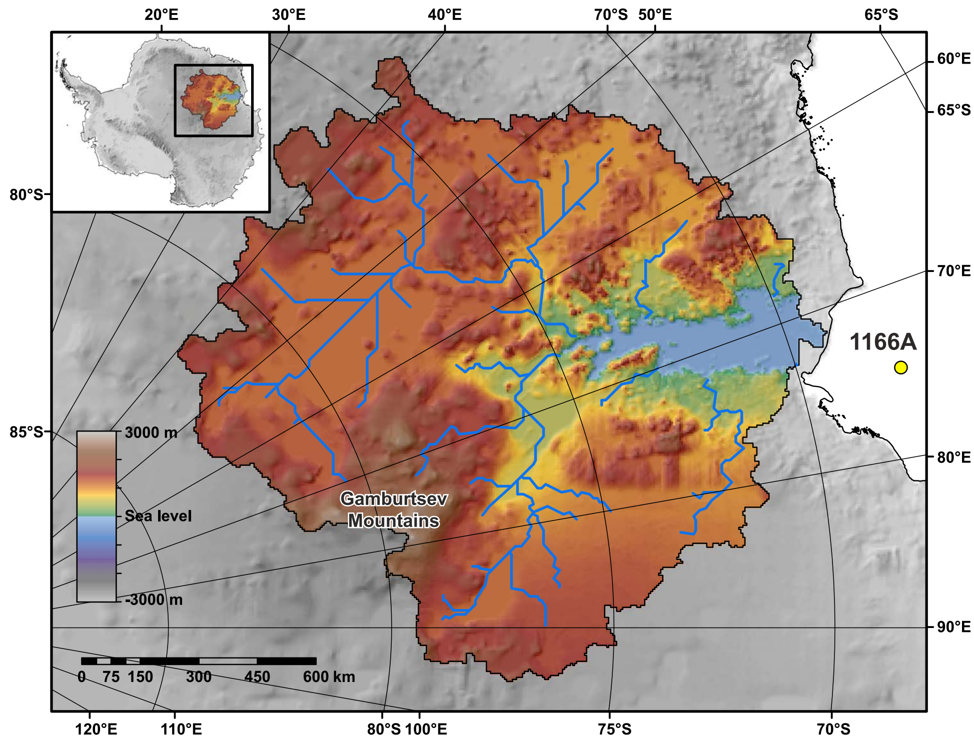

Figure 1. Rebounded Eocene subglacial topography (80 times vertical exaggeration) of the Lambert Graben-Prydz Bay system from BEDMAP data [*Lythe et al.*, 2000] showing the core location used in this study and modeled Eocene pre-glacial drainage into the Lambert Graben [*Jamieson and Sugden*, 2008].

area. Our results imply erosion rates of 0.01–0.02 km/Myr for at least 250 million years.

2. Erosion Rates From Low-Temperature Detrital Thermochronology

[7] Following *van de Flierdt et al.* [2008] we analyzed Eocene fluvial sediments from ODP core 188-1166A [*Cooper and O'Brien*, 2004] from the continental shelf in Prydz Bay (Figure 1). The auxiliary material provides sediment preparation and laboratory methods.[1] Apatite (U-Th)/He (AHe) ages reflect a combination of radiogenic in-growth and time-and temperature-dependent diffusive loss of He. Similarly, apatite fission-track (AFT) ages reflect a combination of radiogenic fission track production and time-and temperature-dependent annealing of accumulated tracks. We take AHe and AFT ages to represent time since monotonic cooling through an effective closure temperature (Tc), which ranges from 40 to 100°C (depending primarily on cooling rate) for the AHe system and is typically 20 to 40°C higher for the AFT system [*Reiners and Brandon*, 2006].

[8] For typical geothermal gradients of about 20 to 30°C/km (typical of a continental interior), modeling using Age2Edot [*Brandon et al.*, 1998] indicates that the apatite will begin to retain helium and fission tracks at closure depths of 1.7–2.5 km and 3.2–4.8 km, respectively. We assume exhumation to be erosional and calculate erosion rates based on AHe and AFT ages. The auxiliary material provides greater detail on the erosion rate calculations. Erosion rates from detrital sediments disproportionately represent the dominant sediment source (most quickly eroding area) in the catchment area and therefore serve as upper limits on basin-wide erosion rates.

[9] The paucity of apatite in these small and valuable ODP core samples led us to employ a novel single grain double-dating approach. We double-dated twenty-four apatite grains using the AHe and AFT systems on each individual grain. AHe ages range from 98 to 377 Ma and AFT ages range from 207 to 612 Ma (see auxiliary material). The average AFT age is 321 Ma, 99 Myr older than the average AHe age of 222 Ma. We subtracted the ~35 Myr depositional age [*Cooper and O'Brien*, 2004] to account for lag time [*Reiners and Brandon*, 2006] for the purpose of erosion rate calculations (Figure 2). These old cooling ages for both systems are consistent with very low bulk regional erosion rates of ~0.01–0.02 km/Myr, or 2.5–5 km of total erosion over 250 Myr.

[10] Single-grain double dates fall into one of two trends that are distinguished by their AFT-AHe age differences. One set ($n = 14$) shows a large spread in AFT ages and a significant AFT-AHe age difference consistent with slow, steady erosion (0.007–0.02 km/Myr) beginning before AFT closure and proceeding to the present. A smaller set ($n = 10$) shows a more restricted range of AFT ages with similar AHe ages, suggesting a pulse of rapid cooling (poorly constrained, but consistent with erosion rates of 0.1 km/Myr) before 250 Ma followed by slow long-term erosion rates as seen in the larger set of grains.

3. Old Grains, Slow Erosion

[11] The data presented here require average erosion rates of at most 0.01–0.02 km/Myr since 250–500 Ma. Such ancient cooling ages and low long-term erosion rates are known in

[1] Auxiliary materials are available in the HTML. doi:10:1029/2010GL045106.

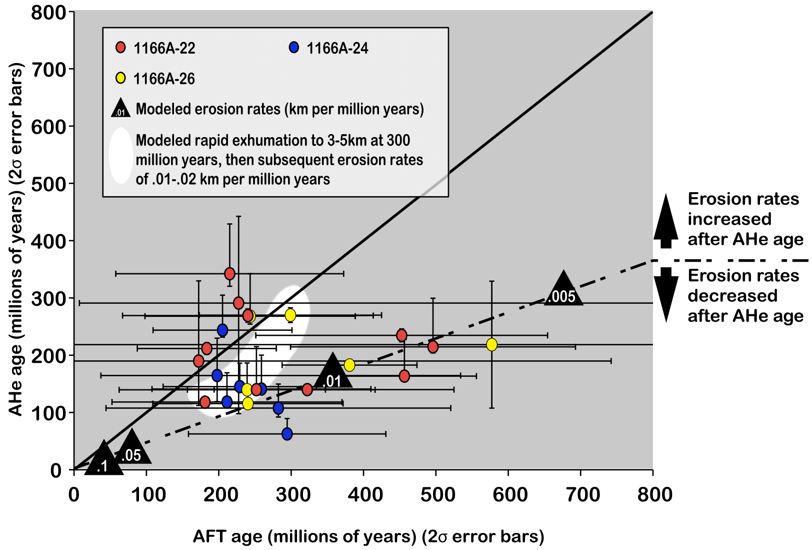

Figure 2. Same-grain fission-track (AFT) and (U-Th)/He (AHe) ages on individual apatite grains (n = 24). The three 1166A samples from ODP leg 188 site 1166A are from ten-meter cores 22, 24, and 26, part of a thick (approximately 110 m) fluvial sand unit of late Eocene age. Data are presented in Tables S1 and S2.

some cratonic settings with extremely low topographic relief like the Canadian Shield [*Lorencak et al.*, 2004]. A broad global correlation between topographic relief and erosion rates has been recognized for decades [*Ahnert*, 1970]. Elevation and relief are stronger controls on both fluvial and glacial erosion than climate or other processes [e.g., *Whipple*, 2009; *Montgomery and Brandon*, 2002]. While the positive relationship in the global dataset exhibits considerable scatter, mountain ranges with comparable relief have modern erosion rates an order of magnitude higher than those inferred for the Gamburtsev Mountains.

[12] The Appalachians have experienced erosion rates of ~0.03 km/Myr for ~200 Ma, but only after Paleozoic erosion rates more than an order of magnitude higher reduced the mountains to less than half the elevation and significantly lower relief than the GSM [*Matmon et al.*, 2003]. The modern GSM have relief more comparable to the <65 Ma European Alps [*Bo et al.*, 2009], which exhibit erosion rates of 0.4–0.7 km/Myr [*Bernet et al.*, 2001]. Far lower long-term erosion rates in the high-relief GSM require long-term tectonic inactivity and an unusual factor such as an exceptionally dry long-term climate or an unusual glacial regime.

[13] The East Antarctic Craton comprises Grenville (1000–1350 Ma) and older provinces permeated by Pan-African metamorphic belts [*Fitzsimons*, 2000; *Boger et al.*, 2002; *Veevers et al.*, 2008a]. The extent and configuration of these features in the interior is poorly constrained; most information about their tectonic history is derived from the edges of the continent. Following Pangaea assembly at 300 Ma and substantial Permo-Triassic rifting, Gondwana breakup after 150 Ma led to only minor rifting on the Lambert Graben margins that produced <200 m of rift sediments offshore and none in the graben [*Lisker*, 2002; *Harrowfield et al.*, 2005; *Lisker et al.*, 2007]. Dominant landscape features that define drainage patterns in East Antarctica are older than 320 Ma [*Dalziel*, 1992; *Veevers*, 1994]. *Arne* [1994] and *Lisker et al.* [2007] proposed Cretaceous rifting around the Lambert Graben based on apatite fission-track thermochronology, but Cretaceous fission-track ages from bedrock are limited to the extreme continental margins. In the interior this interpretation relies on an episode of Cretaceous cooling generated by fairly specific conditions applied to time-temperature modeling of track length distributions. Because not all time-temperature space was explored by *Lisker et al.* [2007] and because our data lack support for such recent cooling, we cannot rule out a complete lack of accelerated Cretaceous erosion.

[14] Permian and Cretaceous coal beds [*Holdgate et al.*, 2005; *Turner and Padley*, 1991] and Mesozoic paleogeography [*Hallam*, 1985] suggest that at least the margins of Antarctica were consistently wet, so it is unlikely that East Antarctica had low erosion rates because of a dry ice-free climate. Uncertainties in the glacial history of Antarctica make the role of glaciers in long-term erosion rates far less clear. While the continental ice sheet that occupied the region for most of the last 34 Myr [*DeConto and Pollard*, 2003] likely maintained extremely low erosion rates with the exception of localized ice-streams, the postulated nucleation of warm-based alpine glaciers in the Gamburtsev Mountains should have locally increased erosion rates by at least two orders of magnitude [*Hallet et al.*, 1996; *Shuster et al.*, 2005; *Smith et al.*, 2007]. If the interior highlands of the Lambert Graben system experienced greatly accelerated warm-based glacial erosion, it must have been short-lived or much less erosive than expected based on modern analogues.

[15] A possible explanation for low long-term erosion rates in high-relief East Antarctica is persistent cover by weakly- or non-erosive high elevation mountain ice caps since before 100 Ma. *Jamieson et al.* [2005] estimated erosion rates for the last 118 Ma as low as 0.001–0.002 km/Myr in the Lambert Graben based on a small sediment pile inconsistent with a rapidly eroding mountain range upstream. Several workers [*Stoll and Schrag*, 1996; *Miller et al.*, 2008] have argued for the presence of mountain ice caps at high elevation in East Antarctica at least as early as the Jurassic (>150 Ma) based on

inferred sea level and ocean chemistry changes. Protection from erosion by mountain ice caps is consistent with other tectonically inactive areas with cold-based glaciers [*Fabel et al.*, 2002; *Staiger et al.*, 2006] and some high latitude active mountain ranges [*Thomson et al.*, 2010]. Extensive long-term glaciation of East Antarctica as a cause of low long-term erosion rates and persistent topography is consistent with the results presented here.

4. Conclusion

[16] The preponderance of Mesozoic and Paleozoic AFT and AHe ages shown here requires that the large East Antarctic catchment area feeding Prydz Bay, including the Gamburtsev Subglacial Mountains and the Lambert Graben, must have undergone very slow erosion since 250–500 Ma. This is consistent with previous findings that there has been no significant tectonic activity in the interior of East Antarctica since the Pan-African (480–600 Ma), and that the Gamburtsev Mountains formed during this event and have endured as tall, high relief mountains despite their antiquity. Calculated basin-wide erosion rates of 0.01–0.02 km/Myr are consistent with long-term preservation of Permian or earlier topography. Our results support the presence of non-erosive mountain ice caps at high elevation since at least 100 Ma. This complements a range of ocean chemistry and stratigraphic evidence that large mountain ice caps must have existed even during the Cretaceous greenhouse world and implies that ice has been an important factor controlling landscape evolution for hundreds of millions of years in Antarctica.

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