Detrital apatite and zircon (U-Th)/He evidence for early formation and slow erosion of the Gamburtsev Mountains, East Antarctica

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Summary The enigmatic Gamburtsev Subglacial Mountains in East Antarctica are important as the postulated source point for Eocene glaciation, but have not been sampled directly because they are covered by 0.6-4 km of ice. Topography and ice flow suggest that they shed terrigenous sediment to the Lambert Graben-Prydz Bay Basin. We measured (U-Th)/He ages of 110 to 316 Ma on detrital apatite grains and 197 to 397 Ma on detrital zircon grains (of pan-African (U-Th)/Pb age) from Prydz Bay cores. Hornblende and biotite $^{40}Ar/^{39}Ar$ ages from these samples cluster around 500 Ma, representing rapid exhumation following the pan-African high grade metamorphism represented in (U-Th)/Pb ages. Combined zircon and apatite (U-Th)/He cooling models require gradual, slow cooling since about 500 Ma with erosion rates of 0.03 km/Ma or less. Models that require rapid uplift and erosion or recent formation of the Gamburtsev Mountains appear to be eliminated by these data.

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Introduction

The Gamburtsev Subglacial Mountains were discovered in 1958 by a Soviet research team during the first International Polar Year. Both the existence of these massive mountains in the absence of known active tectonism and their inaccessible location in the middle of East Antarctica have contributed to their mystery.

Most models of the Eocene-Oligocene glaciation suggest that the ice sheet began in the Gamburtsev Mountains and Dronning Maud Land (DeConto and Pollard 2003). It is, therefore, very important that the structure and erosional behavior of the range be understood in order to understand how the regional topography will be affected by changes to the ice sheet induced by climate change and also how the topography will influence those changes.

Low temperature thermochronology is invaluable in recreating uplift and erosion histories. This provides an important complement to information on high-grade metamorphic events and plutonism, such as provided by the $^{40}Ar/^{39}Ar$ system on hornblende, or the (U-Th)/Pb system in zircons. With closure temperatures of 70°C and 180°C respectively, the apatite and zircon (U-Th)/He systems are sensitive enough to be affected by burial prior to erosion at depths shallow enough to reconstruct recent time-temperature histories. The (U-Th)/He system can be used to document timing of uplift and cooling through the Earth's crust by assuming a geothermal gradient.

Methods

Samples were selected from available sediment cores in Prydz Bay, the body of water at the foot of the Lambert Graben-Prydz Bay Basin. The Gamburtsev Mountains lie at the head of this basin, so drainage through the area is expected to flow primarily from the mountains. Evidence from ice flow charts created by NASA reinforces this conclusion by showing dominant flow into the drainage area from the Gamburtsevs and out of the drainage area into Prydz Bay (NASA 2000). Several cores in the bay have been used for provenance efforts linked to this study. Two of the cores were selected for the first round of helium dating; the 70 cm section from jumbo piston core JPC34 from the *Nathaniel B. Palmer* cruise in 2001 and the 100 cm section from core 26-1W in site 1166A from ODP leg 188. These sites are directly downstream of the mountains through the Lambert Graben. JPC34 contains young glacial diamict sediment from the drainage area and 1166A recovered sediments as old as Cretaceous. The section selected is Eocene fluvial sand expected to have sampled the Gamburtsevs by river runoff prior to Cenozoic glaciation.

Samples were washed through sieves to isolate the >63 μm fraction, then the 63-600 μm fraction was separated by density using both lithium polytungstate (2.85 SG) and methylene iodide (3.3 SG) heavy liquids. The remaining grains were separated magnetically using a Frantz isodynamic separator. Apatite and zircon were picked from the least magnetic portion of the 2.85-3.3 SG and >3.3 SG fractions, respectively. (U-Th)/Pb crystallization ages of the zircon grains are reported by Hemming et al. (2007) for JPC4 and van de Flierdt et al. (2007) for 1166A.

Apatites	Raw Age (Ma)	HAC (correction)	Corrected Age (Ma)	2σ Analytical Error (Ma)	% Error
JPC34 a1	114	0.798	143	7.67	5.35
JPC34 a2	150	0.794	189	10.8	5.73
JPC34 a3	216	0.685	316	16.0	5.08
JPC34 a4	71.1	0.649	110	8.64	7.88
JPC34 a5	191	0.675	283	23.8	8.42
1166A a2	107	0.797	134	12.4	9.26
Zircons	**Raw Age (Ma)**	**HAC (correction)**	**Corrected Age (Ma)**	**2σ Analytical Error (Ma)**	**% Error**
JPC34 z9	155	0.789	197	11.6	5.87
1166A 60 z49	175	0.820	213	9.36	4.39
1166A 60 z65	311	0.851	365	14.6	3.99
1166A 100 z36	294	0.796	369	17.6	4.78
1166A 100 z89	259	0.765	339	15.2	4.50
1166A 80 z16	320	0.807	397	20.1	5.06

Table 1. Measured and corrected ages for all grains, with the HAC (homogeneous α-ejection correction) for each. JPC34 is from cruise NBP01-01 of the *RVIB Nathaniel B. Palmer*. 1166A is core 26-1W from ODP 188-1166A.

After (U-Th)/Pb dating, we removed select grains from the tape mounts for (U-Th)/He analysis. The grains selected were of pan-African age to reflect the dominant age-probability peak in the (U-Th)/Pb ages, the dominant basement of the region (Hemming et al. 2007; van de Flierdt et al. 2007). Due to experimental constraints with the (U-Th)/He process, grains of apatite without visible inclusions were selected and grains of zircon were selected to have a euhedral form. As is typical of detrital samples, this set contained many abraided and broken grains, so selections were not ideal.

Selected grains were measured on two sides under a microscope for volume estimation and then wrapped in foil tubes, niobium in the case of zircon and HF-washed platinum in the case of apatite. After wrapping, the samples were degassed in vacuo under lasers and the helium released was measured by quadropole mass spectrometers.

After He extraction, zircon samples and their Nb wrappers were removed and placed in Teflon tubes in PARR bombs at 225°C with an HF-HNO3 solution and a mixed U-Th spike to dissolve for three days. A Sm spike is used with apatite as well as the U-Th spike due to the much greater contribution of Sm to the helium content of apatite. Apatite dissolved readily in HNO_3 at room temperature and pressure. (Reiners 2005)

After dissolution, samples were analyzed for U and Th (and Sm in the case of apatite) concentrations using an ICP-MS.

The parent (U-Th-Sm) to daughter (He) ratios of each sample were used to calculate raw ages, which were then adjusted to account for alpha particle ejection and diffusion to obtain corrected ages that reflect a true cooling age (Table 1). Richard Ketcham's HeFTy program (Ketcham 2005) was used to further refine the cooling models based on these data into time-temperature paths for each grain based on ejection-corrected ages and diffusion models. HeFTy uses experimentally-determined standard gas diffusion profiles for different minerals to compare projected cooling ages given a user-defined cooling history to actual reported cooling ages. The models can be compared to one another to establish the most likely cooling history, assuming that the samples came broadly from rocks with similar cooling histories. Erosion rates are then

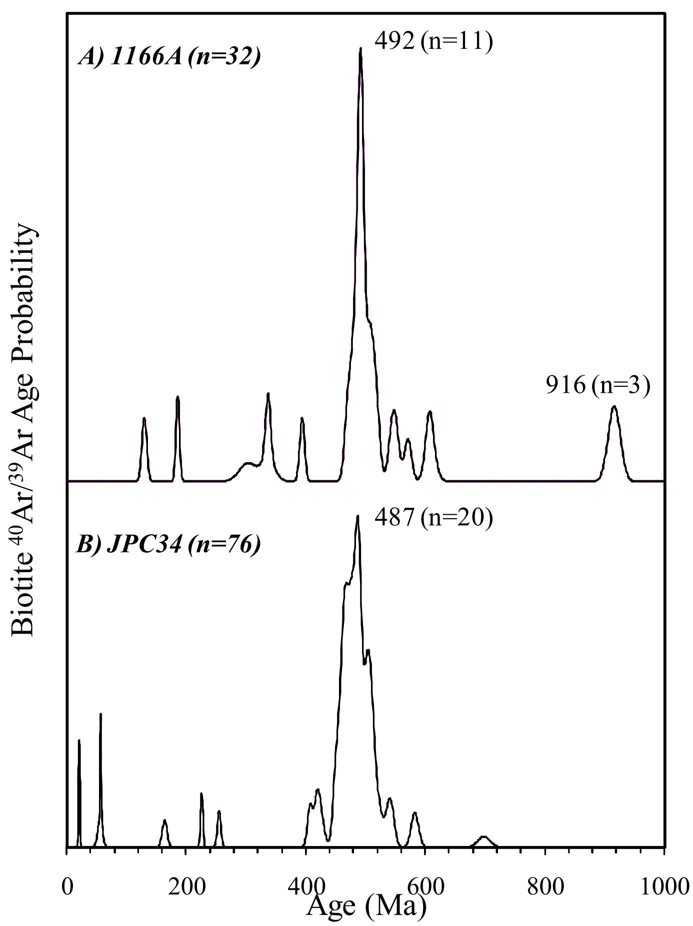

Figure 1. Probability distribution chart showing results from the same samples used here for (unpublished) biotite $^{40}Ar/^{39}Ar$ analysis, with age-probability peaks shortly after 500 Ma.

calculated using a standard geothermal gradient of 25˚C/km.

Results

Apatite grains provided cooling ages of 110 to 316 Ma, while zircon grains provided ages of 197 to 397 Ma. (U-Th)/He ages estimate times of cooling through much lower temperatures than those at which zircon and apatite form. Closure temperatures for these minerals (about 180ºC for zircon and 70ºC for apatite) may be misleading in cases of very slow cooling as diffusion continues, to some degree, in conditions well below the closure temperatures.

In order to account for helium loss from diffusion, HeFTy was used to simulate the effects of diffusion on calculated ages given defined time-temperature paths. Since a limited number of grains were tested and because detrital grains cannot necessarily be attributed to rocks at the same level in the geothermal gradient, models were constructed individually for each grain and then compared as a whole.

Discussion

Corrected ages make clear that the Gamburtsev Mountains are much older than previously thought. (U-Th)/Pb crystallization ages and $^{40}Ar/^{39}Ar$ ages sensitive to metamorphic events all peak around 500 Ma (Hemming et al. 2007; van de Flierdt et al. 2007). Given how old are these cooling ages compared to corresponding (U-Th)/Pb crystallization ages, it is not feasible to create models that support the widely-assumed Gamburtsev history of recent formation and relatively quick erosion. Diffusion models universally indicate that calculated ages paired only with simple closure temperatures underestimate the age of rocks, so even unreasonable models that allow for recent formation or quick erosion are impossible to create.

Recently-collected data indicate rapid cooling to the neighborhood of the 300ºC biotite $^{40}Ar/^{39}Ar$ closure temperature. Biotite grains from both the 1166A and JPC34 samples were analyzed using the $^{40}Ar/^{39}Ar$ method and found to concentrate at 492 Ma and 487 Ma, respectively (Figure 1).

In light of this biotite data, the next time-temperature path attempted was rapid cooling through this temperature and down to the lowest temperature possible given the calculated cooling ages. Clearly this model is not reasonable as it assumes then zero erosion after rapid cooling ends, but it acts as a useful endmember model for continued rapid cooling to temperatures lower than biotite closure. This model works well for the sets of both apatite and zircon grains, but fails for all grains modeled together (Figure 2). With only one of these dating techniques, this model would seem robust, but it is clear when both systems are combined that the Gamburtsevs did not follow this path or that the apatite and zircon grains have fundamentally different sources. The coherence of the higher-temperature thermochronometers does not support large variations in sediment provenance.

Only one endmember model remains: slow, gradual cooling following the pan-African mountain formation event postulated by van de Flierdt et al. (2007) and supported by this study. This model appears moderately robust when apatite or zircon grains are modeled separately, with large ranges among individual grain models possibly attributable to different locations in the geothermal gradient or to variations in erosion rates of different massifs within the mountain. In either case, the differences can be resolved without assuming first order differences in erosion or exhumation history.

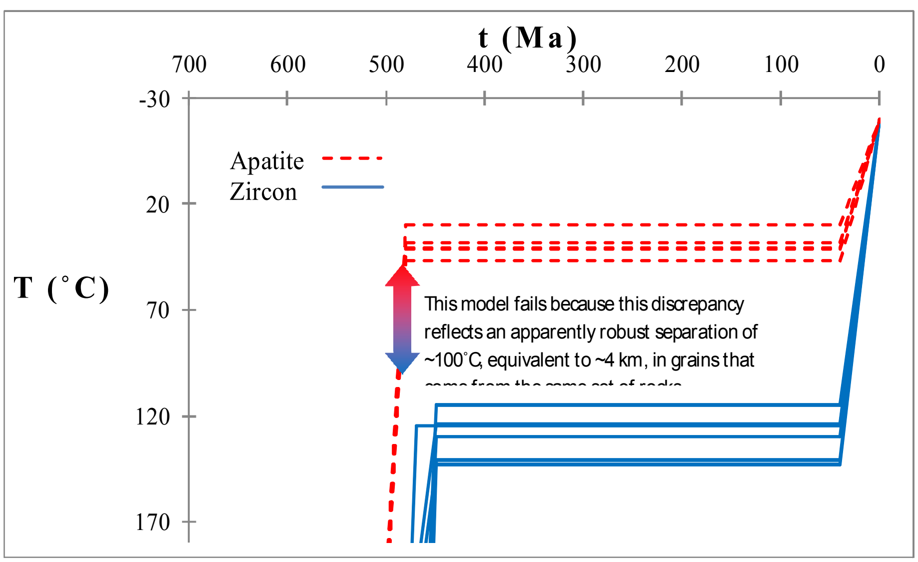

Figure 2. Chart showing the failed zircon and apatite rapid cooling models. Thermal histories such as this can be ruled out because although they explain the apatite and zircon (U-Th)/He ages independently, they would require very different thermal histories for grains that come from the same rock formations.

When apatite and zircon models are placed together (Figure 3), this model actually appears more robust because the spread within each mineral set is strikingly similar. Bimodality is replicated in both samples, but it cannot be determined whether this supports the existence of variably eroding massifs or simply a geothermal variation within the core sample until more samples are available to either reinforce or eliminate the disparity between the two populations.

The model is consistent with the findings of van de Flierdt et al. (2007) that the Gamburtsevs are associated with the major pan-African regional basement. In addition to van de Flierdt's

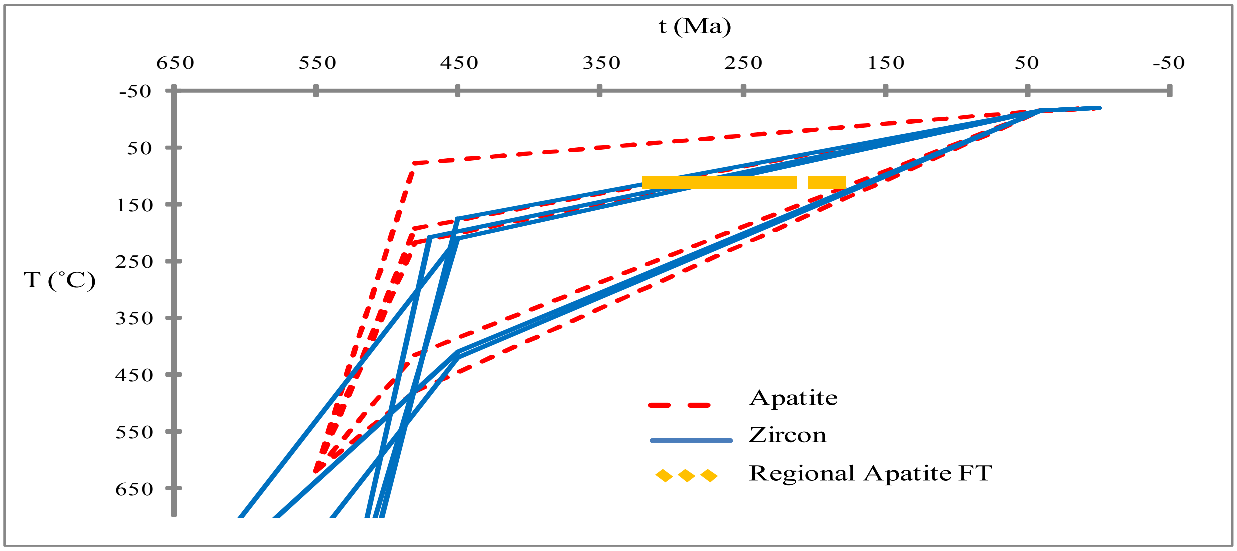

Figure 3. Chart showing the agreement of the apatite and zircon gradual cooling models. Total erosion is 10-18 km (.02-.04 km/Ma) given exposure of grains cooled through 250˚C-450˚C in a geothermal gradient of ~25˚C/km. Overlain regional apatite fission track data is from Lisker et al. (2007).

finding that there is no significant variation in provenance between the mountains and the regional bedrock, the regional apatite fission track data from the nearby Vestfold Hills from Lisker et al. (2007) fit well into the cooling history we modeled for the Gamburtsevs (Figure 3).

Summary

(U-Th)/He and biotite $^{40}Ar/^{39}Ar$ data demonstrate that the Gamburtsev Mountains are of pan-African age and have experienced very slow erosion. (U-Th)/He models demonstrate that ~10-18 km of gradual erosion (~.02-.04 km/Ma; Figure 3) since pan-African formation is the only plausible scenario for the sources of zircon and apatite grains analyzed in this study. Since it is reasonable to assume that some of these grains, if not all, are sourced in the Gamburtsevs, this appears to provide further support for an old age of the Gamburtsevs. Furthermore, the apatite helium ages are all much older than the Eocene-Oligocene glaciation; if the glaciations had exhumed more than 1-2 km of rock, it would have reset these ages. Although more data are clearly needed to make a firm conclusion, the rapid, recent exhumation that would be expected if these mountains were young and quickly eroding was not observed.

There are two endmember scenarios that would produce the sort of history implied by these thermochronology data. In one, the Gamburtsevs began as a taller pan-African mountain range and have eroded very slowly since initial rapid erosion; 10-18 km of erosion (figure 3) translates to a reduction of ~1.7-3.1 km in mean elevation given the ~5/6 isostatic compensation ratio (Molnar and England 1990). In the second scenario, the pan-African Gamburtsevs were roughly as high as they are today and have maintained a steady-state erosion-uplift relationship due to unknown tectonic activity. The first seems more likely, if only because maintaining a gradual, slow uplift for almost five hundred million years seems less plausible than rapid uplift during a major formation event.

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