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Slab window migration and terrane accretion preserved by low-temperature thermochronology of a magmatic arc, northern Antarctic Peninsula

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[1] Existing paleogeographic reconstructions indicate that the northern Antarctic Peninsula was central to several Mesozoic and Cenozoic tectonic events that have implications for ocean circulation and continental margin evolution. To evaluate the exhumational record of these processes, we collected new samples and measured fission track and (U-Th)/He cooling ages of apatite and zircon from 13 Jurassic and Cretaceous granitoids in western Graham Land between the northern tip of the peninsula and the Antarctic Circle. Apatite He data reveal distinct ages and systematic age patterns north and south of Anvers Island, near the midpoint of the study area: To the south, apatite He ages range from 16 to 8 Ma and young northward, whereas to the north they range between 65 and 24 Ma (with one exception at 11 Ma) and young southward. Thermal histories inferred from the ages and closure temperatures of multiple thermochronometers in single samples indicate distinct histories for northern and southern Graham Land. Northern sites reveal a Late Cretaceous pulse of rapid cooling (>7°C/Myr) followed by very slow cooling (~1°C/Myr) to the Recent, whereas southern sites record either a pulse of rapid mid-Miocene cooling (~8°C/Myr) or steady and moderate cooling (~3°C/Myr) from the Late Cretaceous to the Recent. We interpret the Late Cretaceous rapid cooling in the northern part of the study area as a possible manifestation of terrane accretion associated with the Palmer Land event. We interpret the systematic spatial trends in apatite He ages and contrasting thermal histories along the peninsula as recording progressive Late Cenozoic northward opening of a slab window south of Anvers Island. This is consistent with a time transgressive pulse of ~2–3 km of rock uplift and exhumation in the upper plate following ridge-trench collision, cessation of subduction, and opening of the slab window, presumably caused by increased asthenospheric upwelling beneath the overriding plate.

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1. Introduction

[2] Since at least the early Mesozoic, the Antarctic Peninsula has been situated along the continental margin that formed the edge of Gondwana prior to and during its breakup [*Dalziel and Elliot*, 1982; *Lawver et al.*, 1992]. As a result, the geology of the peninsula constitutes a valuable record of Mesozoic-Cenozoic tectonic events that have influenced global ocean circulation [*Lawver and Gahagan*, 2003; *Livermore et al.*, 2005; *Scher and Martin*, 2006], paleoclimate [*Kennett*, 1977; *Miller et al.*, 1987; *Ivany et al.*, 2006], and biogeography [*Regüero et al.*, 2002]. Moreover, because of its central role in the dynamic evolution of the paleo-Gondwanan subduction margin, an understanding of the tectonic history of the Antarctic Peninsula should provide insight into the mechanics of continental margin processes.

[3] One particularly interesting aspect of the peninsula's tectonic evolution is the progressive transition from an active to an inactive subduction zone along its western margin, caused by northward migrating subduction of the Antarctic-Phoenix spreading center (Figure 1). The history of this transition is well constrained in the northern peninsula by magnetic age interpretations of adjacent oceanic crust that record a Miocene to Recent southwest to northeast progression of ridge subduction [*Larter and Barker*, 1991; *Eagles*, 2004; *Breitspecher and Thorkelson*, 2009], presumably causing a time transgressive opening of a window in the downgoing slab. Cenozoic Antarctic Peninsula plate reconstructions are especially reliable as ridge-trench collision events placed one part of the Antarctic plate in contact with another part of the same plate. Thus, postsubduction motion along this "boundary" was essentially zero. Comprehensive tectonic and slab window reconstructions for both southern South America and the Antarctic Peninsula are given by *Breitspecher and Thorkelson* [2009]. Development of a slab window is generally envisioned to cause asthenospheric upwelling beneath the upper plate, and rock uplift, increased heat flux, and related phenomena within the overlying lithosphere [*Delong et al.*, 1979; *Dickinson and Snyder*, 1979; *Lagabrielle et al.*, 2000; *Gorring and Kay*, 2001; *Furlong and Schwartz*, 2004; *Guillaume et al.*, 2009]. The inferred time transgression of slab window opening in this region makes the western Antarctic Peninsula well suited for examining upper plate manifestations of slab window development. In this study we focus on the apatite and zircon (U-Th)/He and fission track thermochronologic record of rocks from the western coast of Graham Land, which record spatial-temporal patterns of cooling associated with exhumation and heat flux changes correlated with the time transgressive cessation of subduction and slab window opening, and may provide insight into the accretionary history of the peninsula.

2. Methods

[4] We collected 14 samples of Jurassic and Cretaceous granitoids from the western coast of Graham Land; nine of these yielded apatite and zircon of sufficient quantity and quality for dating by all thermochronometers used in this study, and four yielded sufficient grains for dating by only some thermochronometers (Figure 2). Extensive snow and ice cover in most locations precluded collecting in subvertical transects to observe age-elevation relationships, so our constraints on cooling rates and interpretations of erosion through time use relative ages of multiple thermochronometers with different closure temperatures. The four thermochronometers used in this study are (1) apatite (U-Th)/He (apatite He) with a closure temperature of ~50–70°C [*Flowers et al.*, 2009], (2) zircon (U-Th)/He (zircon He) with a closure temperature of ~170–200°C [*Reiners et al.*, 2004], (3) apatite fission track (apatite FT) with a closure temperature of ~100–120°C [*Gleadow and Duddy*, 1981], and (4) zircon fission track (zircon FT) with a closure temperature of ~220–260°C [*Brandon et al.*, 1998]. Closure temperatures for each of these systems depend on cooling rate; those employed herein correspond to cooling rates of 1–50°C/Myr. Although we recognize that heat advection in rapidly exhumed regions may bias exhumation histories constrained by multiple thermochronometers [e.g., *Moore and England*, 2001], the relatively slow exhumation rates inferred from our data suggest this effect is minimal in the present study.

[5] Mineral separation was performed by standard crushing, sieving, and magnetic and density sepa-

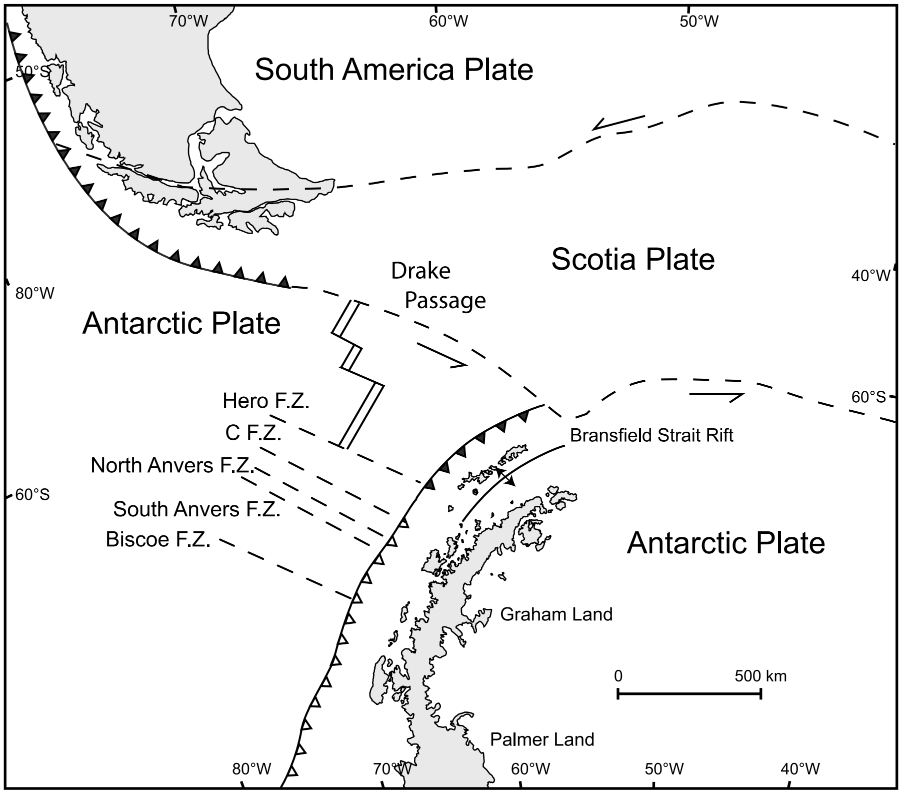

Figure 1. Plate tectonic map of the Antarctic Peninsula and Scotia Arc region. Map symbols are as follows: black sawtooth patterns are currently active subduction zones, white sawtooth patterns are currently inactive subduction zones, white rectangles are currently inactive spreading ridges, and dashed lines are fracture zones (arrows represent motion on transform plate boundaries).

ration procedures. (U-Th)/He analyses were performed at the University of Arizona following methods described by *Reiners et al.* [2004]. Two to five single-grain analyses from each sample were analyzed using Nd:YAG and CO_2 laser heating, cryogenic purification, and quadrupole mass spectrometry for ^{4}He analysis, and isotope dilution high-resolution inductively coupled plasma mass spectrometry (HR-ICP-MS) for U, Th, and Sm (apatite only) analysis. Alpha ejection corrections followed *Farley* [2002] for apatite and *Hourigan et al.* [2005] for zircon. Fission track analyses were conducted at Yale University following methods described by *Thomson and Ring* [2006]. Grains were irradiated at the Oregon State University Triga Reactor, Corvallis, USA and IRMM540R and IRMM541 glasses were used to monitor neutron fluence; zeta calibration factors [*Hurford and Green*, 1983] were 356.8 ± 10.3 (IRMM540R apatite) and 121.3 ± 2.6 (IRMM541 zircon).

[6] Using data obtained through the methods described above, we constructed site-specific cooling histories, which relied partially on thermal history modeling using the HeFTy software package [*Ketcham*, 2005]. Further discussions of HeFTy model parameters are in section 4.1 and the auxiliary material.[1]

3. Results

[7] In Data Sets S1 and S2, we report FT and He data, including weighted mean ages and standard errors for replicate single-grain He analyses, and central ages for FT analyses [*Galbraith and Laslett*, 1993]. In Figure 2 we depict the spatial distribution of apatite He ages, which range from 64 to 8 Ma. The most striking feature of Figure 2 is that all apatite He ages south of Anvers Island are Neogene (8–16 Ma), whereas with the exception of Murray1 (11 Ma), all ages north of Anvers Island are Paleogene (24–65 Ma). Notably, ages are younger with decreasing distance from Anvers Island: South of Anvers Island, He ages decrease systematically to

[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gc/2009gc002765. Other auxiliary material files are in the HTML.

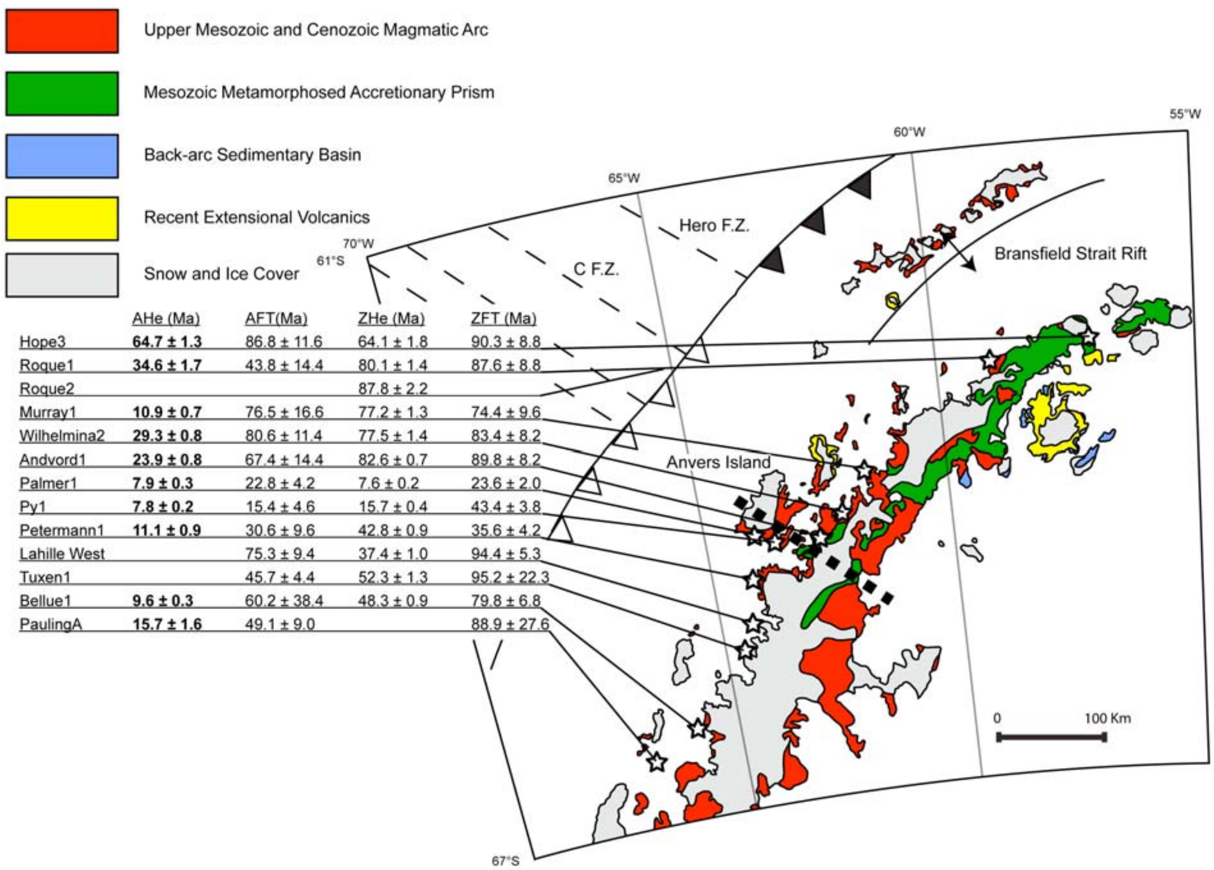

Figure 2. Geologic map of the northern Antarctic Peninsula with sample locations and all apatite and zircon He (AHe and ZHe) and apatite and zircon fission track (AFT and ZFT) ages reported in this study. Light dashed lines represent seafloor fracture zones. Currently active and inactive subduction zones are denoted by black and white saw-tooth patterns, respectively. He ages are weighted means of three to six single-grain aliquots with corresponding 2σ weighted errors. FT ages are central ages with 2σ errors. Heavy dashed black line over Anvers Island denotes inferred domain boundary.

the north, from 16 to 8 Ma, whereas to the north ages decrease systematically to the south, from 65 to 24 Ma.

[8] In Figure 3, we report the apparent thermal histories inferred from combined ages and closure temperatures of each of the thermochronometers, and identify three distinct types of cooling paths. The first is characterized by rapid cooling (>7°C/Myr) in the Late Cretaceous followed by slow cooling (~1°C/Myr) to the Recent; this cooling path is restricted to samples from the northeastern region (Andvord1, Wilhelmina2, Murray1, Roque1). The second type records steady, long-term cooling at moderate rates (~3°C/Myr), and is restricted to the southwestern region (PaulingA, Bellue1, Petermann1). The third type involves an initial phase of slow cooling followed by a pulse of rapid cooling (~8°C/Myr) at circa 15 Ma, and is observed in one sample (Py1), also in the southwestern region. Because closure temperature is partly a function of cooling rate, it is not entirely accurate to interpret a sample's thermal history solely from the closure temperatures of various thermochronometers. Nevertheless, Figure 3 is a useful guide for constructing HeFTy inverse models of a sample's time-temperature ($t - T$) history, a method that we discuss in section 4.1.

[9] The thermal histories of two samples (Roque2, Tuxen1) lack constraints from apatite He ages, so they cannot easily be classified. Based on data from available thermochronometers, however, both samples record apparent cooling paths similar to those of nearby samples, reinforcing the region-specific cooling paths of the study area. Three remaining samples (Lahille West, Palmer1, Hope3) have apatite FT ages older than their corresponding

zircon He ages. These discrepancies cannot be explained, at least in any straightforward way, by typical culprits such as parent nuclide zonation, mineral inclusions, or analytical errors. Nonetheless, Palmer1 and Hope3 have He and/or FT ages requiring rapid cooling in the Late Cretaceous and Miocene, respectively, underscoring the consistency of the regional thermal histories.

4. Discussion

[10] We seek to explain four primary observations of our thermochronologic data: (1) rapid Late Cretaceous cooling in the northeastern study area, (2) young apatite He ages south of Anvers Island, (3) decreasing apatite He ages toward Anvers Island from both the south and north, and (4) distinct thermal histories north and south of Anvers Island.

[11] The crystallization ages obtained for magmatic rocks in the study area, including some of the plutons analyzed herein, suggest that the rapid Late Cretaceous cooling preserved in the northeastern samples of our study resulted from tectonic exhumation. Of the known U/Pb crystallization ages reported for magmatic rocks within ~10 km of our samples [*Tangeman et al.*, 1996; *Pankhurst et al.*, 2000], all are at least 30 million years older, and in some cases 70+ million years older, than the periods of rapid cooling recorded by our samples. Therefore, the rapid cooling rates preserved in the fast cooling subset of our northeastern samples (Figure 3, top) are unlikely to have been caused by thermal relaxation associated with magmatic cooling. Considering plausible thermal diffusivities [*Whittington et al.*, 2009] and geothermal gradients, the rates and magnitudes of cooling recorded in our fast cooling samples of the northeastern part of the study area are more consistent with exhumation [e.g., *Burbank*, 2002].

[12] We interpret this Late Cretaceous rapid exhumation as a manifestation of deformation caused by terrane accretion associated with the Palmer Land Event [*Kellogg and Rowley*, 1989; *Vaughan et al.*,

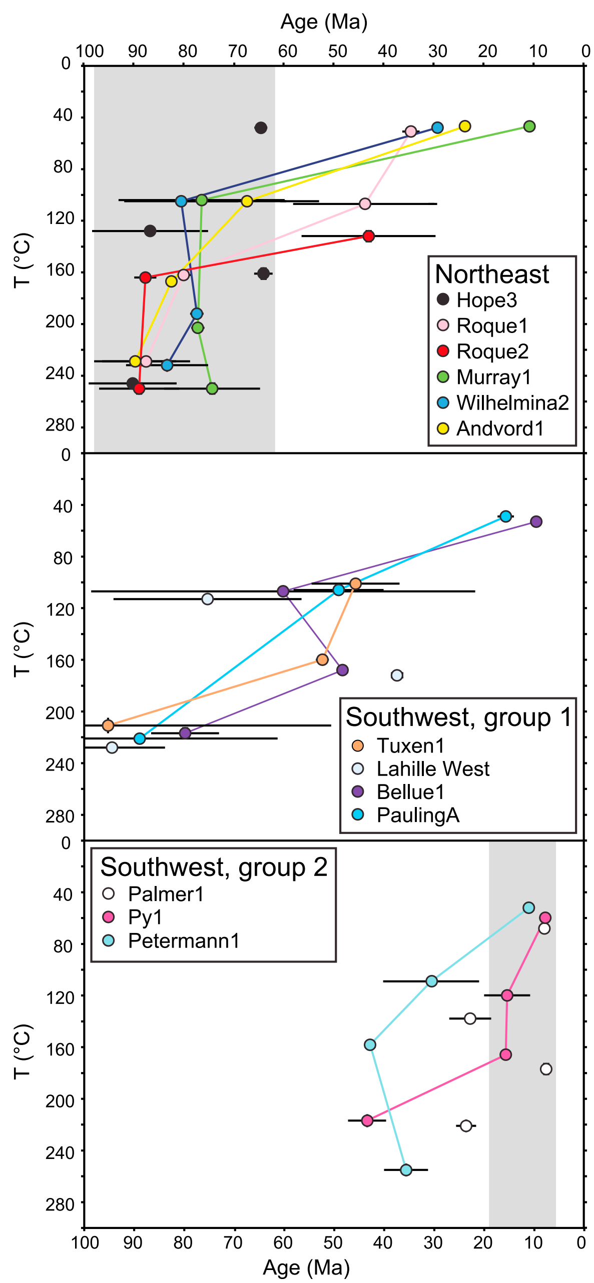

Figure 3. Time-temperature plots based on apatite and zircon (U-Th)/He and fission track thermochronology of all 13 sites examined in this study. The three plots are divided by geographic location: (top) data from all northeastern sites, (middle) data from south of Petermann1, and (bottom) data from all sites between Petermann1 and the South Anvers Fracture Zone. Each point corresponds to a different thermochronologic system: apatite and zircon (U-Th)/He or apatite and zircon fission track. (U-Th)/He ages are reported as weighted mean ages with 2σ standard errors, while fission track ages are central ages quoted with 2σ errors. Closure temperatures and corresponding error bars were calculated using Mark Brandon's CLOSURE computer program (individual error bars may be smaller than their corresponding data point). Closure temperature error was estimated based upon the full range of closure temperature obtained from an estimated range of possible cooling rates through the pertinent interval. Gray bars in Figures 3 (top) and 3 (bottom) represent periods of inferred rapid exhumation. Solid lines connecting data points do not represent absolute $t-T$ paths. The reader is referred to Figure 7 for modeled thermal histories that more accurately describe these paths.

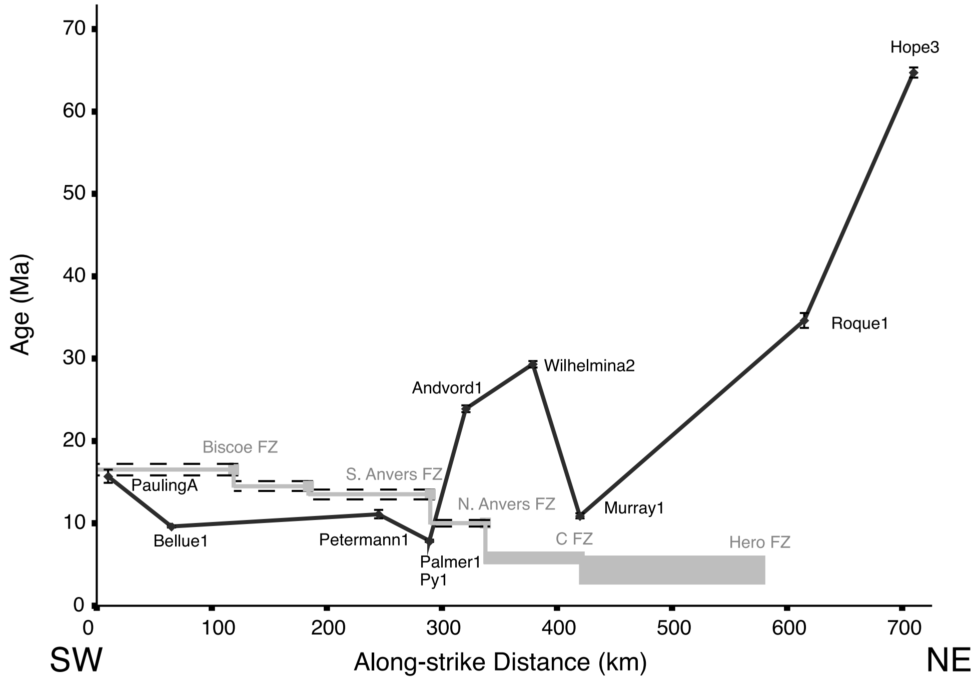

Figure 4. Apatite He age (in black) and ridge subduction age trends (in gray) plotted by along-strike position with respect to the trench of offshore western Graham Land. Seafloor ages are after *Larter and Barker* [1991]. Solid rectangles indicate times of oblique ridge crest–trench collision.

2002a]. Previous studies suggest that the Antarctic Peninsula comprises three geologically distinct regions: the Eastern, Central and Western Domains [*Vaughan and Storey*, 2000]. Whereas the boundaries between these domains are relatively well constrained in the southern peninsula by the Eastern Palmer Land Shear Zone that forms the boundary between the allochthonous Eastern Domain and the parautochthonous or autochthonous Central and Western Domains [*Vaughan and Storey*, 2000; *Ferraccioli et al.*, 2006; *Wendt et al.*, 2008], the northward continuations of these boundaries are unclear in Graham Land. The main phase of amalgamation in the southern peninsula occurred along this shear zone during the Palmer Land Event between 107 and 103 Ma [*Vaughan et al.*, 2002a, 2002b; *Flowerdew et al.*, 2005; *Leat et al.*, 2009]. Most of the ages in our observed pulse of Cretaceous rapid cooling postdate this deformation by roughly 10 to 30 million years, however, the present record of terrane accretion in northern Graham Land is sparse. *Vaughan and Livermore* [2005] reported several episodes of deformation in northern Graham Land with ages ranging from 117 Ma to 90 Ma. These events partially overlap with several of the oldest ages from the northeastern portion of our transect (Figure 3), and might record a northward younging diachronous collision. Although a link between the phase of rapid cooling and events associated with terrane accretion is speculative at this point, our data warrant further study of terrane accretion in the northern part of the peninsula.

[13] The relatively well-documented subduction history of the Antarctic-Phoenix ridge provides an explanation for the latter three of our primary observations. *Larter and Barker* [1991] used the age of seafloor magnetic anomalies adjacent to the remnant Antarctic-Phoenix subduction zone to infer the timing of collision between ridge crest segments of the Antarctic-Phoenix ridge and the trench on the Pacific margin of the Peninsula (Figure 4). Geophysical, geochemical and geologic studies of modern and ancient settings indicate that ridge collision and the subsequent cessation of subduction sometimes produces a lithospheric slab window beneath the upper plate [*Dickinson and Snyder*, 1979] and the northward younging of trench-adjacent seafloor in the northern Antarctic Peninsula suggests that slab window opening proceeded in a similar fashion. In the present configuration, the boundary between the active subduction zone and the inactive margin lies along the Hero Fracture Zone. South of this fracture zone, seafloor ages preserve a history of ridge-trench collision with the youngest

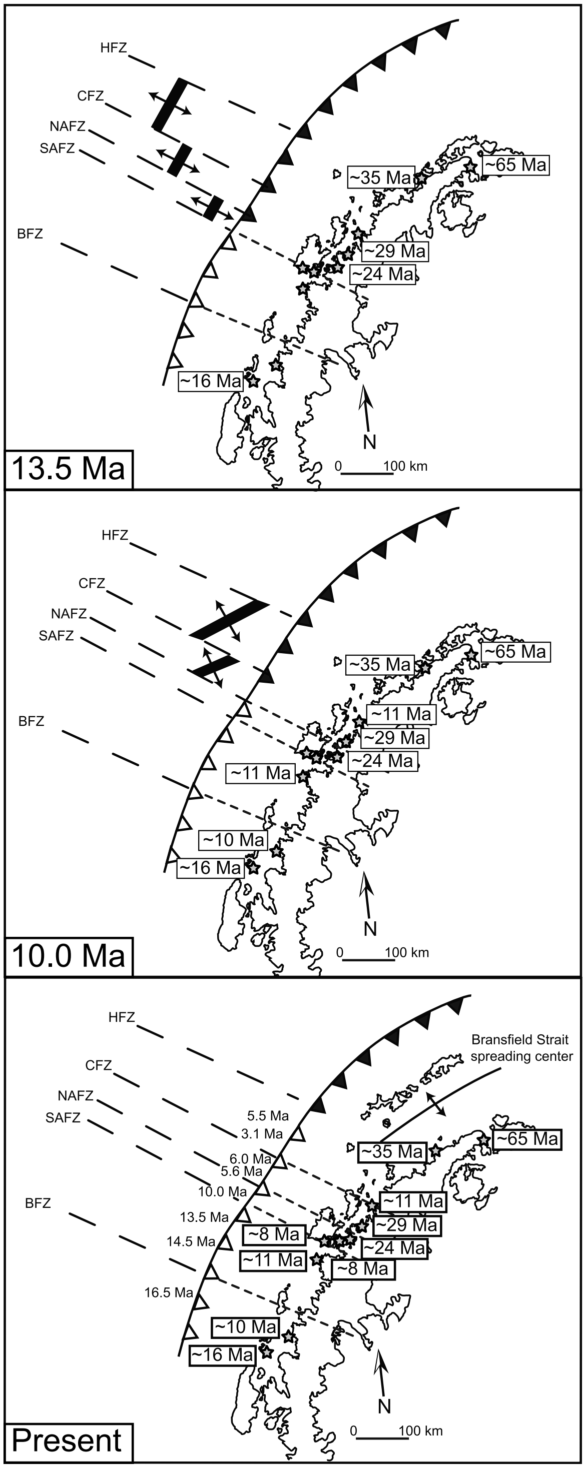

Figure 5. Antarctic Peninsula subduction zone at three different times based on seafloor data of *Larter and Barker* [1991]. Ages in white boxes are approximate apatite He cooling ages for various sites. Solid black rectangles symbolize active spreading ridges, solid black triangles symbolize active subduction, and white triangles symbolize inactive subduction. Ridge crest ages are displayed along the inactive subduction zone in the third panel. Note the rotation of ridge crests at circa 10 Ma.

seafloor age adjacent to the presently inactive trench dating ridge collision and the resultant cessation of subduction. From these observations, *Larter and Barker* [1991] deduced that ridge collision was nearly orthogonal to the trench, occurred in a stepwise fashion as fracture zones offset each section of the spreading ridge, and became progressively younger from the southern part of the peninsula toward the Hero Fracture Zone. Spatial-temporal patterns of alkalic basalts from both trench-proximal [*Hole and Larter*, 1993] and terrestrial locations [*Hole*, 1988] have been similarly interpreted in the context of northward migrating slab window development along the peninsula. We propose that the progressive northward opening of a slab window beneath the southwestern region of Graham Land was accompanied by a time transgressive northward progression of rock uplift and erosional exhumation and a coeval increase in basal heat flux associated with the alkalic basaltic magmatism.

[14] Replacement of cold subducting lithosphere with hot subslab asthenosphere in the slab window may have several upper plate manifestations. These include changes in the volume, location, and geochemistry of arc magmatism [*Hole*, 1988; *Cole and Basu*, 1992; *Hole and Larter*, 1993; *Dickinson*, 1997; *Yogodzinski et al.*, 2001]; increased heat flux at the base of the upper plate [*Delong et al.*, 1979; *Iwamori*, 2000] and initiation of rock uplift [*Ramos*, 2005; *Lock et al.*, 2006; *Lagabrielle et al.*, 2000; *Guillaume et al.*, 2009]. Mechanisms that cause rock uplift include an increase in shortening rates at the time of ridge-trench collision [*Ramos*, 2005], isostatic responses to lower crustal thickening [*Cloos*, 1993], dynamic responses to asthenospheric upwelling [*Dickinson and Snyder*, 1979], or a combination of isostasy and dynamic flow [*Furlong and Govers*, 1999]. As a result, northward migrating ridge-trench collision and slab window opening would likely produce a northward progression of rock uplift south of the Hero Fracture Zone. As shown in Figures 4 and 5, apatite He ages young northward, in parallel with adjacent seafloor ages along the formerly active subduction margin. This age correlation is noteworthy as it supports a causal relationship between cessation of subduction and slab window opening along the trench. As ridge-trench collision progressed northward, sites in the southwest passed through the closure temperature for apatite He approximately 1–7 Myr after the spatially equivalent collision event.

[15] The systematic northward younging of apatite He ages is disrupted by a shift in ages between

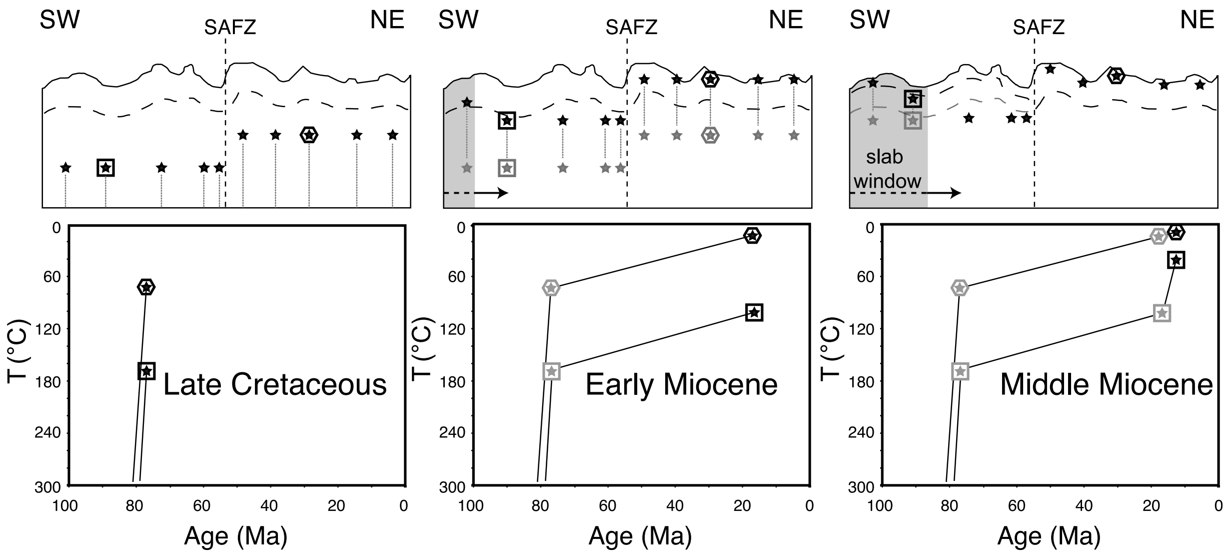

Figure 6. Schematic exhumation pattern along-strike of the Antarctic Peninsula. Horizontal dashed curve represents the apatite He closure isotherm. Light gray shapes track the movement of samples and the apatite closure isotherm through time. Arrow denotes direction of the opening slab window. Vertical dashed line in each cartoon represents the South Anvers Fracture Zone and the divide between the northeastern and southwestern regions. Plots directly beneath each time slice represent the expected $t - T$ history for a sample in either the northeastern or southwestern region, given the tectonic conditions.

samples Py1 and Andvord1 at the approximate position of the South Anvers Fracture Zone, as emphasized in Figure 4. Although the South Anvers Fracture Zone is not the modern boundary between active and inactive subduction, slab window opening probably did not occur north of this fracture zone, as discussed further below.

4.1. Modeled Time-Temperature Histories

[16] In order to examine the cooling trends for our samples in the context of the development and evolution of a slab window, we present schematic Cretaceous-Recent $t - T$ histories for the northeastern and southwestern regions (Figure 6). In these plots, one representative sample from each region is presented as a single $t - T$ pathway shown in three successive time slices. By circa 80 Ma, samples now at the surface in the northeast were exhumed to shallower depths than those presently at the surface in the southwest. Following the rapid Cretaceous cooling experienced by the northeastern samples, both regions experienced roughly similar slow cooling until the Miocene. In the Miocene, opening of the slab window in the southwest caused uplift due to isostatic and/or dynamic effects of slab removal and asthenospheric upwelling [*Guillaume et al.*, 2009], resulting in greater exhumation than in the northeast. Whereas this phase of Miocene cooling in the southwest could be solely a result of erosional exhumation resulting from surface uplift, a component of the rapid Miocene cooling could also be explained by thermal relaxation following the increased heat flux expected of slab window opening.

[17] In order to estimate the amount of exhumation necessary to produce the spatial patterns in apatite He ages and thermal histories, we inversely modeled $t - T$ histories for eight samples (those with apatite He ages and reasonable cooling paths) using HeFTy [*Ketcham*, 2005]. We modeled both apatite He and apatite FT ages for all eight samples. Our models included fission track length data, although this information was available for only four samples: Murray1, Wilhelmina2, Petermann1, and PaulingA (Figure S1). Zircon He data was also modeled for all samples except PaulingA, which had no acceptable zircon for He dating. HeFTy is best suited as a tool for testing the numerical validity of user-specified thermal histories. To this end, we employed an iterative approach to our modeling whereby the inverse model constraints for a given sample were determined by matching forward modeled and observed cooling trends (Figure 3) while maximizing the number of viable cooling paths (see auxiliary material for method details). For two of the northeastern sites (Roque1and Andvord1), HeFTy generated numerous viable $t - T$

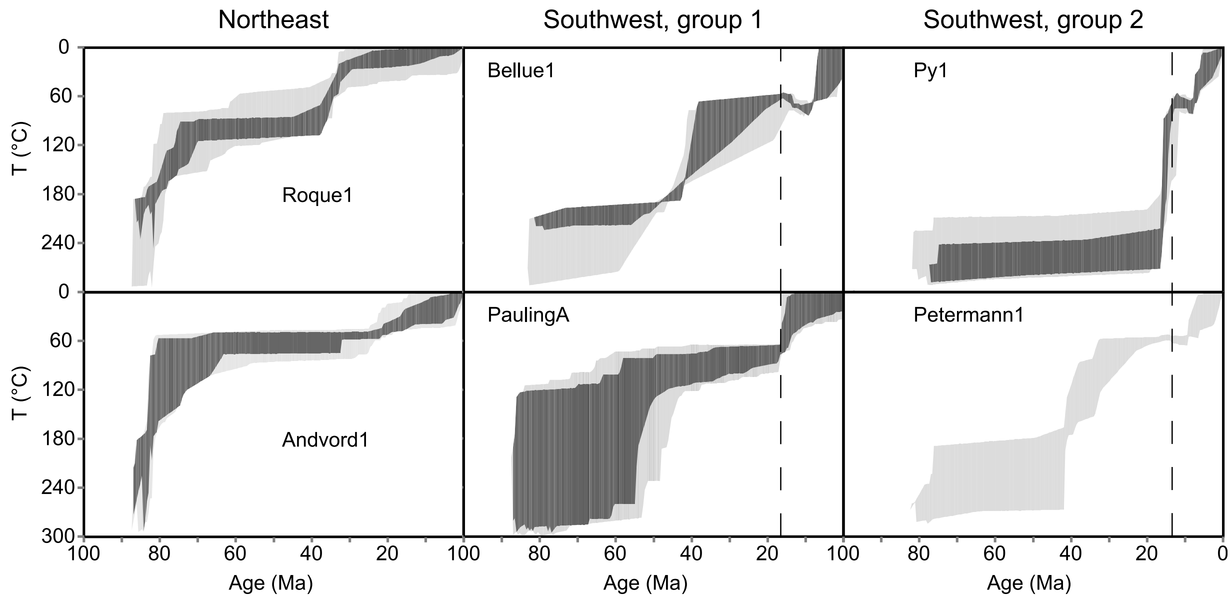

Figure 7. Results from HeFTy inverse models. Plots are arranged into groups in a fashion similar to Figure 3 and depict the cumulative envelopes for all samples in each geographic location. Opacity of the envelopes is based upon the goodness of fit (GOF), with GOF > 0.05 in light gray and GOF > 0.5 in dark gray. See *Ketcham* [2005] and the auxiliary material for details on HeFTy statistical methods.

paths from our constraints (Figure 7), demonstrating that our interpretations of monotonic cooling trends following rapid Cretaceous cooling for this domain are reasonable and do not require either reheating or a significant increase in Cenozoic cooling rates. The other two sites (Murray1 and Wilhelmina2) do not generate viable $t - T$ paths for the given constraints when all data parameters are used and are thus not presented in Figure 7. When the fission track length data is excluded, however, acceptable paths are found. Although HeFTy is unable to model all thermochronologic aspects of Murray1 and Wilhelmina2, we argue that the age data from these two samples still conforms to our interpretation of cooling trends for the northeastern region.

[18] Modeling results from the southwestern sites (PaulingA, Bellue1, Petermann1, and Py1), however, are more complex (Figure 7). Our forward modeling suggests that, assuming a 25°C/km geothermal gradient, exhumation of ~2–3 km during a late phase of erosion could adequately explain the combined data. However, of the five samples, only PaulingA generated viable paths using an inverse model of 2 to 3 km of exhumation at the time of ridge crest–trench collision alone, whereas the others required a component of reheating. Results from another series of forward models indicate that 3 km and 2 km exhumation end-members would require increased geothermal gradients of 28°C/km and 42°C/km, respectively, in order to satisfy the model constraints. Presumably, the increased heat flux accompanying slab window development could account for these elevated geotherms (see auxiliary material). We also used forward modeling to determine the time interval for this reheating and obtained a best fit range of 0–5 Myr for the lag between ridge crest-trench collision and reheating. When employed as constraints in our inverse models, these time and temperature parameters yield viable cooling paths for the four remaining samples. In summary, the general pattern of modeled cooling in the southwestern domain consists of relatively slow cooling from 80 Ma to the time of ridge crest-trench collision, followed by either 2–3 km of relatively rapid exhumation (PaulingA), or 2–3 km of relatively rapid exhumation with an elevated geothermal gradient of 28–42°C/km (Bellue1, Petermann1, and Py1).

[19] The thermal and erosional histories derived from a combination of forward and inverse HeFTy models are not unique solutions but rather viability tests for the hypothesis of increased exhumation rates at about the time of ridge-trench collision. Topographic differences between the southwest and northeast regions of the peninsula may provide further evidence in support of our hypothesis as surface topography in slab window settings has been linked to dynamic rock uplift [e.g., *Guillaume et al.*, 2009]. We expect that the kilometer-scale

differences in exhumation between the northeast and southwest region predicted by our models would produce similar disparities in topography. Previous studies have noted that the topography of the Antarctic Peninsula's inner plateau resembles a planar bedrock erosion surface, which rises from an average elevation of 900 m at the northern tip to an average elevation of 1750 m at roughly 65° S [*Elliot*, 1997; *Smellie et al.*, 2009]. This latitude is noteworthy as it approximately corresponds to our inferred domain boundary. South of this latitude the plateau remains at a more or less constant elevation. Present-day topography is not necessarily a consequence of Miocene uplift, however, *Smellie et al.* [2009], on the basis of the stratigraphy of glacial-derived sediments on James Ross Island, suggested that significant uplift of the inner plateau took place by the mid-late Miocene. These observations are consistent with our model results and strengthen our hypothesis that slab window development led to kilometer-scale rock uplift in the southwestern region of the peninsula. An additional insight from our HeFTy models is that explaining the relatively young ages and apparently rapid cooling in the southwestern domain by any amount of erosional exhumation less than ~2 km would require a transient heating pulse producing a geothermal gradient of ~60°C/km in the uppermost ~5 km of the crust.

[20] Although a combination of slab window induced uplift and an increase in basal heat flux can account for the apatite He age patterns in both domains, some aspects of the data require further consideration. First, whereas ridge crest-trench collision occurred north of the South Anvers Fracture Zone, apatite He ages in samples from this region are considerably older than the near-trench seafloor ages and therefore do not appear to record a response to slab window development (Figure 4). The distribution of seafloor ages [*Larter and Barker*, 1991] offers an explanation. Shortly after the 10 Ma collision of the ridge crest segment between the North and South Anvers Fracture Zones, the vestiges of the Phoenix plate underwent clockwise rotation (Figure 5). Because of the young and buoyant oceanic lithosphere involved in subduction, rotation may have been an expression of large intraplate contrasts in the buoyancy of the subducting slab [*Cloos*, 1993]. Such buoyancy contrasts could have caused a tear in the downdip portion of the slab, leaving behind young plate segments that were difficult to subduct. In turn, these slab fragments may have shielded the upper plate from an influx of asthenospheric material, thus preventing the full opening of a window. Regardless of cause, changes to the subduction zone geometry, as reflected in trench-proximal seafloor ages, occurred north of Anvers Island and provide a logical explanation for the change in the thermochronologic record between the southwestern and northeastern parts of the study area.

4.2. Use of Thermochronology in Slab Window Settings

[21] Our data reveal spatial and temporal correlations between the tectonic evolution of the trench margin and cooling ages of rocks within the Peninsula that are consistent with a time transgressive pattern of exhumation. More focused sampling could reveal exhumation rates through time (e.g., with vertical transects), providing a more complete understanding of these correlations. Because our ability to make connections between regional thermochronology and ridge crest-trench collision is a consequence of detailed seafloor magnetic anomaly analysis, our methods should offer geodynamic insights in areas with similarly well-defined margin histories [e.g., *Furlong and Schwartz*, 2004].

[22] A comparison between our preferred model of slab window development for the Antarctic Peninsula and other slab window settings offers perspective on this utility. Information from seafloor ages [*Larter and Barker*, 1991] suggests that, south of the North Anvers Fracture Zone, the angle of plate convergence between the Antarctic and Phoenix plates relative to the trench was nearly orthogonal and postsubduction motion along the passive plate boundary was essentially zero. In contrast, other sites of past and present slab windows along the eastern Pacific margin, namely Alaska, California, and Chile, show more complex plate interactions. In each setting, the angle of ridge-trench convergence is oblique and a minimum of three plates are involved in the process [*Dickinson and Snyder*, 1979; *Haeussler et al.*, 2003; *Breitspecher and Thorkelson*, 2009]. These styles of subduction lead to an unzipping pattern whereby slab window geometry is triangular and the opening progressively widens as the ridge descends into the mantle [see *Thorkelson*, 1996, Figure 10]. Additional complexities may develop when three or more plates, each with independent motion vectors, compose an evolving slab window. For example, transverse motion between the Pacific and North America plates may have sutured the plate boundary off the coast of California after ridge-trench collision. In this instance, ridge-trench collision did not necessitate slab window devel-

opment, as plate detachment occurred at a level too deep to affect the continental lithosphere [*Bohannon and Parsons*, 1995]. Each type of slab window, from the relatively simple (Antarctic Peninsula) to the complex (coastal California), should produce a unique style of uplift that reflects a window's geometry and evolution. We argue, therefore, that the spatial patterns of thermochronologic cooling ages in such settings should provide valuable constraints and complementary evidence for the shallow crustal and surficial manifestations of asthenospheric and lithospheric responses to slab window development.

[23] In the case of the Antarctic Peninsula, our data agrees with previous models of slab window geometry south of the North Anvers Fracture Zone [*Hole and Larter*, 1993], however, we see no thermochronologic signal of slab window opening north of this fracture zone, despite continued ridge-trench collision. These results advance the suggestion of *Bohannon and Parsons* [1995] that slab windows are not always the necessary consequence of a ridge-trench collision and may, in some instances, be kinematically implausible. Furthermore, our data demonstrates that, although early ridge-trench collision events led to slab window opening beneath the Antarctic Peninsula, the system may have evolved such that the downgoing plate stalled as ridge-trench collision proceeded. Due to this interesting evolution, the Antarctic Peninsula documents both an apparently simple slab window development, as well as complexities that arose as the system matured. Although some ambiguity remains as to whether our data represent an exhumation or reheating signal, our study indicates that low-temperature thermochronology of subduction-related rocks offers a useful complement to existing methods of assessing slab window formation and migration [*McCrory and Wilson*, 2009], and should thereby allow assessment of tectonic and geologic models that infer slab window formation, such as those suggested for the North America Cordillera [*Dickinson and Snyder*, 1979; *Thorkelson and Taylor*, 1989; *Bohannon and Parsons*, 1995], southern Patagonia [*Ramos and Kay*, 1992], Central America [*Johnston and Thorkelson*, 1997], the Sunda-Java system [*Whittaker et al.*, 2007] and Alaska [*Cole and Stewart*, 2009].

5. Conclusions

[24] Thermochronologic data from western Graham Land of the Antarctic Peninsula reveal two domains with distinct Cenozoic thermal histories, providing insight into upper crustal responses to (1) terrane accretion and (2) time transgressive shifts from active to inactive subduction along the plate margin caused by the opening of a slab window. Samples from the northeastern region record rapid cooling in the Late Cretaceous followed by slow cooling to the Recent, which we interpret as a result of exhumation caused by terrane accretion associated with the Palmer Land Event. Southwestern samples record either steady cooling since the late Cretaceous or slow Paleogene cooling followed by rapid Neogene cooling.

[25] Apatite He ages contain systematic trends along the peninsula, with younger ages in the southwestern region that young toward the latitude of Anvers Island, just north of which ages are significantly older. These data both demonstrate differential cooling across the peninsula and document late Cenozoic interactions between the Antarctic and Phoenix plates. Principally, we suggest that the opening of a slab window in the southwestern region caused ~2–3 km of rapid exhumation due to rock uplift associated with slab removal, asthenospheric upwelling, and some contribution from increased heat flux.

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