Ross Sea mylonites and the timing of intracontinental extension within the West Antarctic rift system

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ABSTRACT

There are few direct constraints on the timing and style of faulting in the Ross Sea sector of the West Antarctic rift system, although Cretaceous plate reconstructions indicate that Ross Sea extension between East and West Antarctica occurred prior to breakup of the Gondwana margin ca. 80 Ma. Mylonitic gneisses dredged from the eastern Ross Sea indicate shear-zone deformation considerably earlier, at 98–95 Ma. Strain analysis of fabrics indicates 85%–100% extension. Overprinting brittle structures record translation of shear-zone gneisses into the upper crust. Samples yield sensitive high-resolution ion-microprobe U-Pb zircon ages of 102–97 Ma, correlated to Byrd Coast Granite onshore, and concordant $^{40}Ar/^{39}Ar$ biotite and K-feldspar ages of 98–95 Ma, indicating that granites were mylonitized soon after emplacement and cooled rapidly. Apatite fission-track data corroborate this rapid cooling event, and reveal a second rapid cooling event ca. 80 Ma. Evidence for contemporaneous deformation and a similar thermal evolution at Deep Sea Drilling Project Site 270 on the Ross Sea central high and for a migmatite dome on land attests to the regional extent of intracontinental extension. Extension occurred at a time of complex microplate interactions along the Cretaceous active Gondwana margin, suggesting that distributed deformation in the overriding Antarctic plate may be related to plate boundary dynamics.

Keywords: West Antarctica, intracontinental extension, thermochronology, U-Pb SHRIMP, mylonite.

INTRODUCTION

The Ross Sea is a 1200-km-wide embayment that forms part of the West Antarctic rift system between East and West Antarctica (Fig. 1) (LeMasurier, 1990; Behrendt et al., 1991). Marine geophysics images north-trending basins and bedrock highs in subsided Ross Sea crust, and high-angle faults cutting sedimentary strata of uncertain age (Cooper et al., 1991; Davey and Brancolini, 1995; Luyendyk et al., 2001). Airborne geophysics shows that the structures continue east into thinned (23–25 km) continental crust of Marie Byrd Land (Luyendyk et al., 2003). The vast region east of the Transantarctic Mountains (Fig. 1) has undergone 300–500 km of extension (Fitzgerald et al., 1986; Luyendyk et al., 1996). Despite its size, at 2.25×10^6 km^2 comparable to other large rift provinces, only indirect evidence from paleomagnetic research (DiVenere et al., 1994; Luyendyk et al., 1996) and plate reconstructions (Lawver and Gahagan, 1994; Stock and Cande, 2002) is used to infer the timing of the main phase of Ross Sea extension, and debate is ongoing over the comparative importance of Mesozoic versus Cenozoic events (e.g., Stock and Cande, 2002).

In this paper we present direct evidence for the structural style and precise timing of a shear zone in the West Antarctic rift system. We determine a mid-Cretaceous granite emplacement age for the mylonitic gneiss protolith using sensitive high-resolution ion microprobe (SHRIMP) U-Pb zircon analysis, and provide close age constraints for the subsequent ductile to brittle structural progression using $^{40}Ar/^{39}Ar$ biotite and K-feldspar and apatite fission-track (AFT) thermochronology. The samples, obtained by dredge from Colbeck Trough, eastern Ross Sea (Fig. 1), record rapid cooling attributable to tectonic exhumation, and offer direct support of a detachment model for the West Antarctic rift system during the Cretaceous (Fitzgerald and Baldwin, 1997). The shear zone and coeval structures developed during waning subduction (Mukasa and Dalziel, 2000) and complex microplate tectonics (Larter et al., 2002) along

Figure 1. Cretaceous West Antarctic rift system and restored position of New Zealand–Campbell Plateau ca. 105 Ma. Colbeck Trough sample location (77°18′02.0″S, 158°31′02.0″W) borders Edward VII Peninsula (EP). CH—central high; 270—Deep Sea Drilling Project Site 270; FM—Fosdick Mountains. Campbell Plateau configuration is after Sutherland (1999).

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the convergent Gondwana margin prior to breakup of the margin, suggesting the possibility that ridge-trench interactions drove intracontinental extension within the overriding Antarctic plate.

GEOLOGIC BACKGROUND

In Marie Byrd Land (Fig. 1), ocean and ice conceal the structures that accommodated relative motion between Marie Byrd Land and East Antarctica (Luyendyk et al., 1996). Petrologic evidence for extension comes from a 110–100 Ma mafic dike swarm (Storey et al., 1999), from 102–95 Ma anorogenic plutons of the Byrd Coast Granite (Weaver et al., 1992), and from mid-crustal exposures in the Fosdick Mountains, rapidly exhumed and cooled between 105 and 94 Ma ($^{40}Ar/^{39}Ar$; Richard et al., 1994). There is no record of the Jurassic tholeiitic magmatism (Fleming et al., 1997) that marks the onset of Gondwana breakup in East Antarctica, and the main phase of Ross Sea extension postdates the opening of Weddell Sea (König and Jokat, 2003) between East and West Gondwana by more than 50 m.y.

AFT data from onshore and offshore sites record the duration and show the areal extent of Cretaceous tectonism. AFT data from the Fosdick Mountains (Fig. 1) indicate rapid cooling ca. 95 Ma, then slow cooling until 80 Ma, followed by rapid cooling during exhumation ca. 80 Ma (Richard et al., 1994). Onshore near Colbeck Trough, AFT vertical profiles suggest gradual cooling of shallow-level Byrd Coast intrusions, followed by rapid exhumation ca. 75 Ma (Lisker and Olesch, 1998). Calc-silicate basement gneiss cored offshore at Deep Sea Drilling Project (DSDP) Site 270 (Fig. 1) yields a dominant AFT age component of 90 ± 6 Ma and a minor component of Jurassic age (Fitzgerald and Baldwin, 1997). Geological evidence, including brittle-upon-ductile textures in the gneiss and the presence of sedimentary breccia, led Fitzgerald and Baldwin (1997) to propose a detachment fault model for Late Cretaceous extension in the Ross Sea.

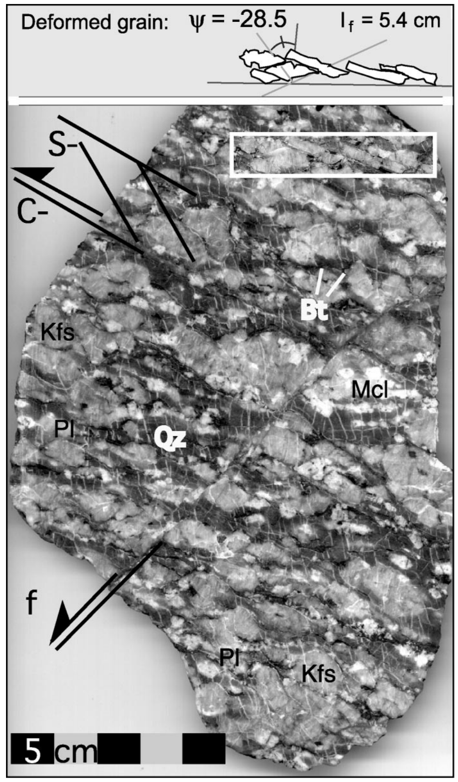

Figure 2. Mylonitic gneiss D2-83 cut parallel to mineral lineation and perpendicular to foliation, illustrating mixed brittle and ductile feldspar and quartz fabrics. Monoclinic shape fabrics and C-S fabric are defined by ribbon quartz (Qz), biotite (Bt), K-feldspar (Kfs), and plagioclase (Pl), and show top-to-left shear sense. Brittle fault (f) with consistent kinematic sense cuts foliation. White patchy texture is millimeter-scale microcline (Mcl) replacing orthoclase. White box surrounds bookshelf feldspar used to quantify strain. Sketch of grain (top) restores to original length of 2.9 cm for change in line length of 2.5 cm, equivalent to extension, *e* = 86%. Angular shear, ψ, in example equates with shear strain, $\gamma = \tan \psi = 0.54$. Range of values for studied grains is *e*, 86%–130% and γ, 0.54–1.1.

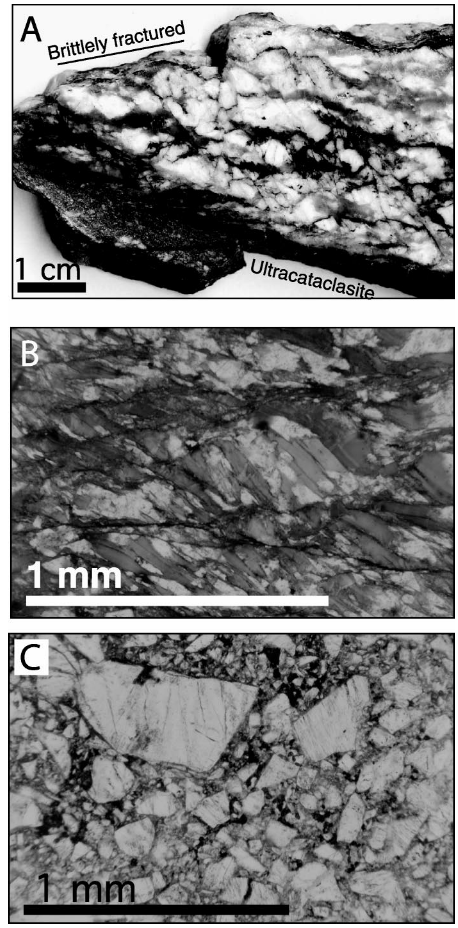

Figure 3. Photomicrographs illustrating brittle textural overprint. A: Ultracataclasite vein in hand sample. B: Chloritic microbreccia, foliated and cut by brittle shears. C: Microbreccia. Textures record progression from mixed brittle-ductile to brittle conditions, suggesting upward translation of mylonitic gneisses to shallow crustal levels.

MYLONITIC GNEISSES FROM COLBECK TROUGH

Well-lineated mylonitic gneisses were dredged from 663–497 m depth from the bedrock escarpment bounding Colbeck Trough (Fig. 1). Of 103 samples, 83 are mylonitic granitic gneiss (Fig. 2) of uniform composition and texture. Clasts are subangular to angular and lack facets or scratch marks. These characteristics, and a high cable tension sustained during dredging (>12,000 kg), convince us that the samples are not a random group of glacial erratics but were recovered from, or near, their bedrock source. The Colbeck Trough formed through glacial incision of sediment and bedrock on the Ross Sea continental shelf (Luyendyk et al., 2001), likely in the Holocene, since retreat of the glacial grounding line to its present position has occurred there since 3.3 ka (Stone et al., 2003).

Samples exhibit mixed brittle and ductile feldspar and ribbon quartz fabrics (Fig. 2), typical of mylonitic shear zones developed at temperatures <500 °C (e.g., Passchier and Trouw, 1998). Large K-feldspar augen (>1 cm in length) are brittlely fractured and attenuated by incremental displacements between grain segments, forming bookshelf texture. A simple strain analysis using attenuated feldspars (Fig. 2, inset) determines 85%–125% extension and shear strain, γ, from 0.54 to 1.1. Foliation is cut by discrete faults with 1–2 cm of displacement (Fig. 2), black ultracataclasite (Fig. 3A), and microbreccia (Fig. 3B). The textures record a progression from mixed brittle-ductile to brittle conditions.

Mineral textures were examined to assess the extent of dynamic recrystallization of biotite and K-feldspar (orthoclase microperthite) to be used for $^{40}Ar/^{39}Ar$ thermochronology. Fresh biotite occurs within strain shadows adjacent to K-feldspars, as mica fish within quartz ribbons, or as polycrystalline packets draping microfault steps upon bookshelf feldspars. The textures indicate syntectonic growth of biotite. In K-feldspar, breakdown products (sericite, myrmekite) are rare to absent, but there is evidence for recrystallization. Samples D2-3 and D2-70 contain Carlsbad-twinned orthoclase cut by close-spaced microfractures and almost completely replaced by microcline with crosshatch twin-

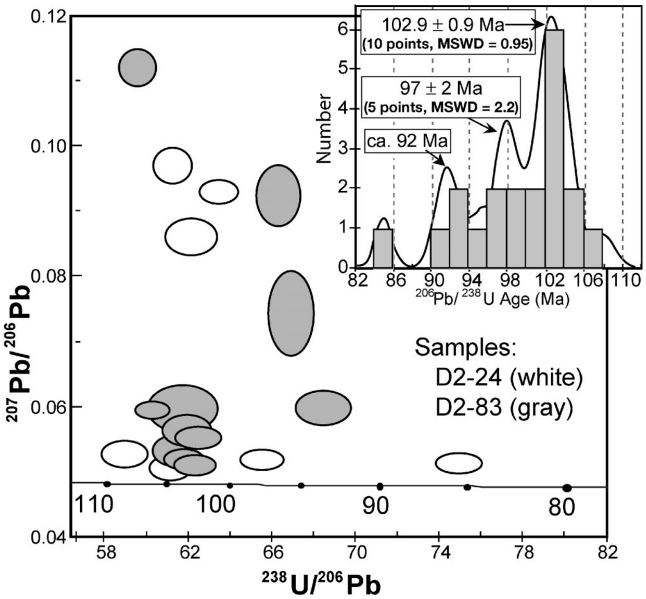

Figure 4. Tera-Wasserburg concordia plot of in situ sensitive high-resolution ion microprobe zircon U-Pb data, calibrated but uncorrected for common Pb. Analyses are plotted as 1σ error ellipses. Two analyses significantly enriched in common Pb are excluded. Inset is combined relative probability plot with stacked histogram for ^{206}Pb/^{238}U ages (^{207}Pb corrected). Major magmatic peak is at 102.9 ± 0.7 Ma, with subordinate peaks at 97 ± 2 Ma and 92 Ma inferred to reflect periods of zoned rim growth and/or radiogenic Pb loss. Data and cathodoluminescence images are available (see footnote 1 in text). MSWD—mean square of weighted deviates.

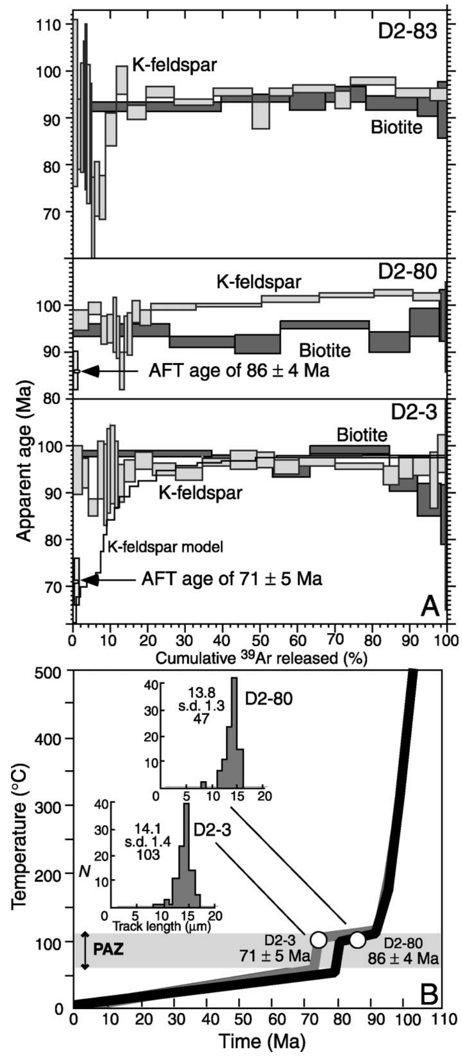

Figure 5. A: ^{40}Ar/^{39}Ar biotite and K-feldspar spectra for samples D2-3, D2-80, and D2-83; apatite fission-track (AFT) ages for D2-80 and D2-3 are noted. Thermal history in B was used to obtain model K-feldspar D2-3 spectra. Data and analytical procedures are available (see footnote 1 in text). B: Time vs. temperature trajectories based on integrated ^{40}Ar/^{39}Ar and AFT data sets. AFT length histograms suggest decrease in rate of cooling between ca. 90 and 80 Ma, after formation of mylonites, followed by another period of rapid cooling ca. 80–70 Ma. PAZ—partial annealing zone.

ning, evident as a macroscopic patchy white texture (Fig. 2).

ISOTOPIC INVESTIGATIONS AND THERMOCHRONOLOGY

U-Pb Geochronology Results

To establish protolith age, we obtained 18 in situ SHRIMP zircon analyses from two polished thin sections (Table DR1[1]). Cathodoluminescence images (Fig. DR1; see footnote 1) and transmitted- and reflected-light photomicrographs were used to determine the textural setting of individual zircon grains. As a result, the zircon population was subdivided into >150 μm prismatic igneous grains included within biotite and K-feldspar and <50 μm granular grains that occur along grain boundaries or biotite cleavage planes.

A dominant cluster of ages from prismatic grains provides a weighted mean ^{206}Pb/^{238}U age of 102.9 ± 0.7 Ma (Fig. 4). Intermediate and younger U-Pb age populations correspond to zircon rims or tiny zircon grains along grain boundaries. Five analyses of the rims or tiny grains have a weighted mean ^{206}Pb/^{238}U age of 97 ± 2 Ma; three other analyses form a less well-defined group ca. 92 Ma (Fig. 4).

^{40}Ar/^{39}Ar and Apatite Fission-Track Thermochronometry

K-feldspar and biotite from three texturally uniform samples were used for ^{40}Ar/^{39}Ar thermochronometry (Table DR2; see footnote 1) in order to constrain the cooling history. The ^{40}Ar/^{39}Ar biotite spectra are complex, with oldest apparent ages from 98 to 95 Ma. K-feldspar results are generally concordant with biotite (Fig. 5A). Sample D2-80 produced somewhat older ^{40}Ar/^{39}Ar K-feldspar apparent ages of 102.7–95 Ma from domains of primary orthoclase. Two of the three samples yielded sufficient apatite for AFT analysis (Table DR3; see footnote 1). AFT ages are 86 ± 5 Ma for sample D2-80 and 71 ± 5 Ma for sample D2-3; mean track lengths are 13.8 μm and 14.1 μm, respectively (Fig. 5B). Both samples pass the χ^2 test, indicating that grains represent a single age population.

DISCUSSION

The ^{206}Pb/^{238}U age of 102.9 ± 0.7 Ma from prismatic zircons is interpreted as the crystallization age of the granite protolith, determined to be Byrd Coast Granite, now known as a constituent of the thinned continental crust forming the Ross Sea. We interpret the ^{40}Ar/^{39}Ar ages of syntectonic biotite to date the timing of mylonitization between 98 and 95 Ma. Thus, mylonitization closely followed granite emplacement. Because intermediate ages for small zircons situated along grain boundaries are within the 98–95 Ma range, we infer that the zircons existed in settings susceptible to localized strain and fluid circulation during mylonitization, and that their ages record new zircon growth or Pb loss from existing small grains (e.g., Wayne et al., 1992). We interpret the concordant ^{40}Ar/^{39}Ar biotite and K-feldspar ages of 98–95 Ma as a record of rapid cooling following mylonitization.

The rapid thermal evolution, degree of strain, and brittle-upon-ductile textures are consistent with upward translation into the realm of brittle cataclasis during tectonic denudation (e.g., Lister and Davis, 1989), in agreement with a detachment model for Ross Sea extension (Fitzgerald and Baldwin, 1997). The AFT data reveal some complexity in the

[1]GSA Data Repository item 2004008, tabulated sensitive high-resolution ion microprobe zircon, ^{40}Ar/^{39}Ar and fission-track data, cathodoluminescence images of zircons, and explanation of analytical procedures and modeling, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

cooling history that cannot be explained by a single rapid event. The AFT ages are significantly younger than $^{40}Ar/^{39}Ar$ K-feldspar ages, suggesting slowed cooling after 95 Ma; yet the long mean track lengths indicate rapid transit through the apatite partial annealing zone (110–60 °C). Similar $^{40}Ar/^{39}Ar$ and AFT results come from the Fosdick Mountains, which underwent rapid cooling between 105 and 94 Ma, slow cooling, then renewed accelerated cooling through the partial annealing zone between ca. 80 and 75 Ma (Richard et al., 1994). AFT data from Edward VII Peninsula, adjoining Colbeck Trough (Fig. 1), also define early (92 $\pm$ 4) and late (80 $\pm$ 4 to 72 $\pm$ 5 Ma) cooling events (Lisker and Olesch, 1998). The dominant AFT age component from DSDP Site 270, 90 $\pm$ 6 Ma (Fitzgerald and Baldwin, 1997), corresponds to the early cooling event.

CONCLUSIONS

Our results and available evidence from across the region indicate two intervals of tectonism, a first at before 90 Ma and a second ca. 80–71 Ma. Mylonitic gneisses formed during the first event provide direct evidence of mid-crustal shear zones and detachment faults active at 98–95 Ma, during development of the West Antarctic rift system. Within 8 m.y. of its emplacement at 103 Ma, Byrd Coast Granite was mylonitized and cooled through biotite and K-feldspar $^{40}Ar/^{39}Ar$ closure temperatures. The close correlation of $^{40}Ar/^{39}Ar$ and AFT cooling ages for shear-zone rocks with gneiss cored at DSDP Site 270 and rapidly exhumed migmatites on land in the Fosdick Mountains indicates that the detachment systems evolved rapidly over a wide region.

We conclude that deformation occurred during detachment faulting that led to opening of the Ross Sea, and was completed prior to breakup between the Campbell Plateau of New Zealand and Marie Byrd Land and onset of seafloor spreading at 79 Ma (Stock and Cande, 2002). The AFT evidence for the younger rapid cooling event ca. 80 Ma most likely reflects denudation associated with the breakup event.

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