Two-stage rifting of Zealandia-Australia-Antarctica: Evidence from ^{40}Ar/^{39}Ar thermochronometry of the Sisters shear zone, Stewart Island, New Zealand

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ABSTRACT

The Sisters shear zone is a newly discovered Late Cretaceous detachment fault system exposed for 40 km along the southeast coast of Stewart Island, southernmost New Zealand. Footwall rocks consist of variably deformed ca. 310 and 105 Ma granites that range from undeformed to protomylonite, mylonite, and ultramylonite. The hanging wall includes non-marine conglomerate and brittley deformed granite. K-feldspar thermochronometry of the footwall indicates moderately rapid cooling (20–30 C°/m.y.) due to tectonic denudation over the interval ca. 89–82 Ma. Return to slow cooling at 82 Ma coincides with the age of the oldest seafloor adjacent to the Campbell Plateau and reflects the mechanical transition from continental extension to lithospheric rupture and formation of the Pacific-Antarctic Ridge. Our findings support a two-stage rift model for continental breakup of this part of the Gondwana margin. Stage one (ca. 101–88 Ma) is the northward propagation of continental extension and the Tasman Ridge as recorded in mylonite dredged from the Ross Sea and the Paparoa core complex. Stage two (ca. 89–82 Ma) is extension between the Campbell Plateau and West Antarctica leading to formation of the Pacific-Antarctic Ridge.

Keywords: New Zealand, extension, thermochronology, Gondwana, rifting, Cretaceous.

INTRODUCTION

Plate reconstructions of Mesozoic Gondwana place Zealandia (New Zealand and surrounding continental shelf, e.g., Mortimer, 2004) at the Pacific margin, adjacent to southeast Australia and West Antarctica (e.g., Sutherland, 1999; Eagles et al., 2004). Much attention has been directed toward extension between western Zealandia and eastern Australia leading to opening of the Tasman Sea (Tulloch and Kimbrough, 1989; Etheridge et al., 1989; Spell et al., 2000) and rift-related deformation in Marie Byrd Land, West Antarctica, and the adjacent Ross Sea (e.g., Luyendyk et al., 2003; Siddoway et al., 2005). These studies have outlined the timing and style of extension and breakup between Australia and Zealandia, and of extension between East and West Antarctica. This paper focuses on the outstanding problem of the nature and timing of extension in eastern Zealandia leading to Pacific-Antarctic Ridge formation and separation of the Campbell Plateau from West Antarctica.

Field observations and ^{40}Ar/^{39}Ar data from the Sisters shear zone on Stewart Island, southernmost New Zealand, are presented here as evidence for a Late Cretaceous detachment fault system that accommodated continental extension and thinning of the Campbell Plateau and was kinematically linked to formation of the Pacific-Antarctic Ridge. The timing of extension and the transition from continental rifting to seafloor spreading is documented using ^{40}Ar/^{39}Ar thermochronometry, which indicates that this event is 5 to 10 m.y. younger than extension documented in the Ross Sea and western New Zealand. Our new results and observations, combined with published thermochronology data from western New Zealand and West Antarctica, reveal a sequence of extensional tectonism that can be best explained by a two-stage model for breakup of the Pacific margin of Gondwana.

SISTERS SHEAR ZONE, STEWART ISLAND

Stewart Island is part of the Median batholith and Western Province of New Zealand (Fig. 1). The Median batholith represents a magmatic arc that developed above the paleosubduction zone along the Gondwana Pacific margin (Tulloch and Kimbrough, 2003). Major structures on Stewart Island include the northwest-striking Freshwater fault zone, Escarpment fault, and Gutter shear zone. These structures are related to pre-breakup convergent margin tectonism and have been described by Allibone and Tulloch (1997, 2004). In contrast, the Sisters shear zone, located along the southeast coast and oriented obliquely to these structures, is here interpreted to represent an extensional detachment fault system.

The Sisters shear zone is exposed along the southeast coastline of Stewart Island for ~40 km (Fig. 1). At some localities, it is as wide as 5 km (map view); however, the boundaries are not well constrained due to relatively poor exposure. The shear zone occurs within Carboniferous and Early Cretaceous granitic rocks that exhibit varying degrees of deformation from essentially undeformed to protomylonite, mylonite, and ultramylonite, with widespread but generally minor brittle deformation overprints. Shear bands, oblique-grain-shape fabrics, sigma- and delta-type feldspar porphyroclasts, and mica fish indicate shear sense.

The Sisters shear zone is divided into two segments based on the nature of ductile fabrics, predominant kinematics, and along-strike offset of the western boundary of ductile fabric (Fig. 1). The northern segment of the shear zone typically consists of granite mylonite and protomylonite with foliations dipping 20–30ºSSE and top-to-the-southeast shear sense. Footwall rocks there are locally overprinted by southeast-dipping brittle normal faults, commonly subparallel to the ~060° strike of the foliation. In the southern segment, foliations are generally less well developed than in the north, and deformation tends to be localized into 5–50-m-thick high-strain zones including ultramylonite. Ductile kinematic indicators in the southern portion exhibit both top-to-the-northwest and top-to-the-southeast downdip shear sense, but brittle normal faults are consistently top-to-the-southeast. Stretching lineations throughout the shear zone consistently trend 330/150° ± 15°. Because of apparent along-strike offset of the western boundary of ductile fabric and differences in kinematics and foliation attitudes, we infer that the north and south segments of the shear zone are separated by a transfer fault (e.g., Lister et al., 1986) (Fig. 1).

Microstructures in the deformed granites indicate greenschist facies metamorphic conditions followed by decreasing temperatures during shearing. In thin section, quartz exhibits features of plastic deformation including oblique-grain-shape fabrics in dynamically recrystallized grains (regime 2 of Hirth and Tullis, 1992) and ribbons with patchy to undulose extinction, whereas feldspars exhibit dominantly brittle deformation. The lack of postdeformational growth in ~30 µm grains of recrystallized

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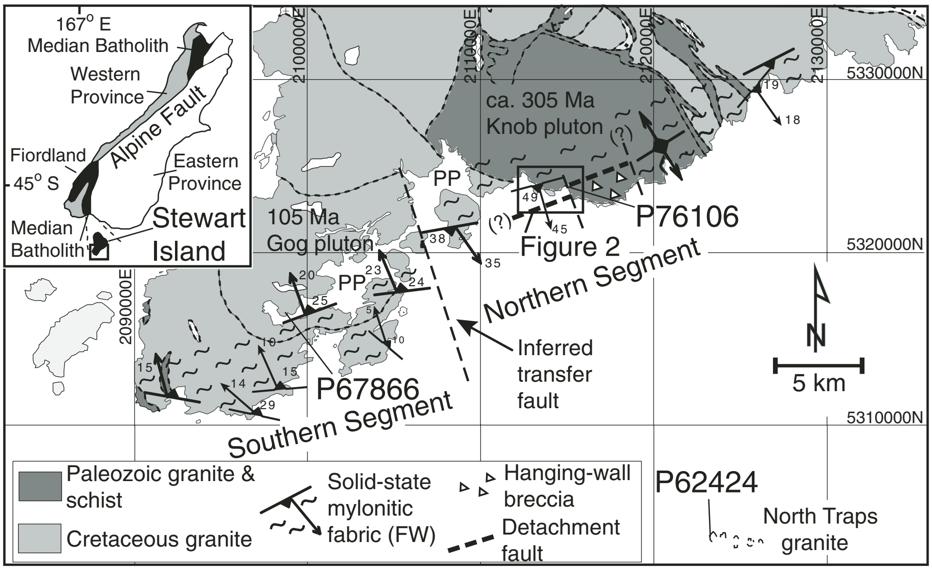

Figure 1. Generalized geologic map of southern Stewart Island (modified from Allibone and Tulloch, 2004) showing dominantly plutonic nature (Median batholith—black in inset). Note distribution of ductile fabric, stretching lineation orientation, and inferred transfer fault (see text). Sample locations are labeled with P-numbers (PETLAB database (http://data.gns.cri.nz/pet/). North Traps are a set of low-lying rock and reefs consisting of undeformed granite. Box indicates area of Figure 2. Eastings and northings conform to the New Zealand Map Grid (NZMG). PP—Port Pegasus.

quartz, preservation of unrecovered quartz ribbons with undulose extinction, and cataclastic "crush zone" overprinting collectively indicate cooling during deformation.

A brittle detachment surface oriented 061/27°S is exposed in a small bay in the northern segment opposite of Sisters Islets (Fig. 2). A 10-cm-thick black flinty ultracataclasite underlies the fault surface and separates mylonite of the footwall from chloritic hydrothermally altered and brecciated granitic rocks of the hanging wall. Slickenlines measured on the detachment surface are of the same trend as stretching lineations throughout the shear zone. The detachment fault surface appears to be entirely offshore in the southern segment of the shear zone (Fig. 1).

The Sisters Islets, a pair of ~200 × 400 m islets ~1 km offshore (Fig. 2), are composed of essentially undeformed conglomerate (Fleming and Watters, 1974) and represent the hanging wall of the Sisters shear zone. Conglomerate beds on the Sisters strike ~070°, dip 20–25°NNW, and consist of rounded, with lesser subangular, dominantly granitic clasts enclosed in an arkosic sandstone matrix. Many clasts exhibit ductile fabric; however, a provenance from the footwall rocks has not yet been confirmed.

^{40}Ar/^{39}Ar THERMOCHRONOMETRY

Samples were collected from granitic outcrops at locations shown in Figure 1 and detailed in the PETLAB database (http://data.gns.cri.nz/pet/). The ^{40}Ar/^{39}Ar analyses were conducted at the Nevada Isotope Geochronology Laboratory at University of Nevada–Las Vegas (UNLV); data tables and descriptions of analytical methods are given in appendices DR1 and DR2 in the GSA Data Repository.[1]

Footwall Mica Ages

Muscovite and biotite were collected from footwall rocks from the Knob pluton in the northern segment ~50–100 m below the detachment surface (P76106, Fig. 1). Muscovite yielded a relatively flat age spectrum with a plateau age of 93.8 ± 0.4 Ma (uncertainties 2σ), incorporating 96% of the gas released (Fig. 3A). Biotite yielded a plateau age of 90.0 ± 0.8 Ma (59% of the gas released) and an isochron age of 90.6 ± 1.2 Ma with a ^{40}Ar/^{36}Ar intercept of 294.5 ± 2.2, indicating no excess ^{40}Ar in the sample.

Footwall and Hanging-Wall K-Feldspar

Three K-feldspar separates were analyzed using detailed furnace step-heating, including isothermal duplicates, to determine Ar diffusion kinetics for application of multiple diffusion domain (MDD) thermal modeling (Lovera et al., 1989, 1991). Two samples were collected from footwall rocks: P76106, (discussed previously), and P67866 from the western side of the southern segment of the shear zone (Fig. 1). The footwall samples yielded maximum ages of 89–90 Ma, and sample P76106 exhibited a prominent age gradient over the initial gas release that was absent in sample P67866 (Fig. 3A). The third sample (P62424) was collected from hanging-wall granite of North Traps (ca. 120 Ma, U-Pb zircon; Allibone and Tulloch, 2004), 35 km southeast of the coast (Fig. 1). This sample yielded maximum ages ca. 25 Ma older than the footwall samples. Following an initial age gradient over the first 10% of the gas release, the age spectrum flattened at 115–116 Ma, close to the granite crystallization age.

Thermal History of the Sisters Shear Zone

The muscovite (93 Ma) and biotite (90 Ma) footwall ages and "nominal" closure temperatures of 400 and 350 °C (cf. McDougall and Harrison, 1999), respectively, yield a crude cooling rate estimate of ~17 °C/m.y. The two footwall K-feldspars (P76106 and P67866) (Fig. 3) yield similar MDD modeling results (Fig. 3B). Both show moderately rapid cooling (20–30 °C/m.y.)

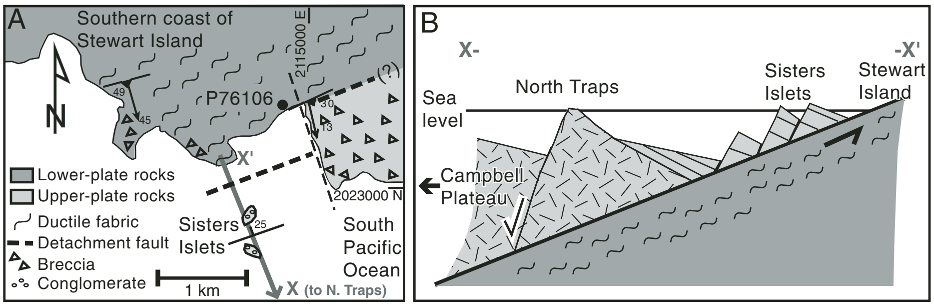

Figure 2. A: Stewart Island coast opposite Sisters Islets showing outcrop relationships of ductile fabrics, chloritic breccia, and conglomerate of Sisters Islets. X-X′ line marks section line for B. B: Schematic cross section depicting upper- and lower-plate relationship between Sisters Islets, North Traps, and Stewart Island coast.

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[1] GSA Data Repository item 2007099, Table DR1 (^{40}Ar/^{39}Ar data tables), Appendix DR2, (textural documentation of shear zone samples), and Appendix DR3 (analytical procedures for ^{40}Ar/^{39}Ar analyses and summary of K-feldspar MDD modeling), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

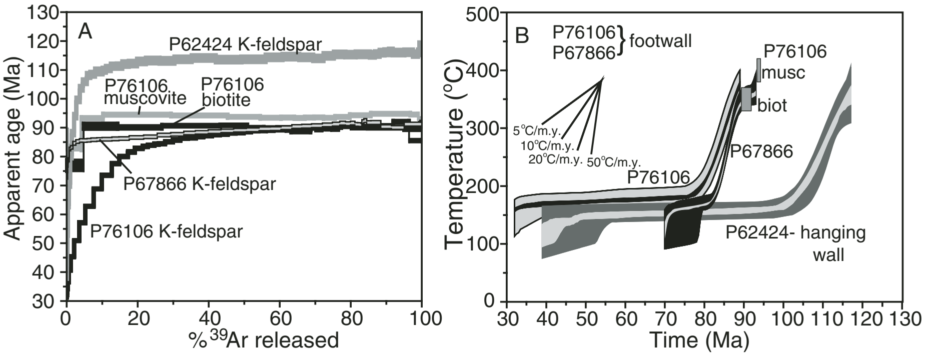

Figure 3. A: Age spectra from samples P76106, P67866 (footwall), and P62424 (hanging wall) (Fig. 1) (uncertainties 1σ). B: Comparison of thermal histories from footwall and hanging-wall samples (see text). Outer envelope of curves indicates 90% confidence interval for distribution of obtained thermal histories; inner envelope indicates 90% confidence interval for median.

beginning at ca. 89 Ma, followed by a transition to very slow cooling at ca. 82–78 Ma (Fig. 3).

Hanging-wall sample P62424 yields a distinctly different thermal history from those of the footwall samples. Rapid cooling from 116 to 105 Ma following emplacement at ca. 120 Ma likely reflects conductive thermal re-equilibration with the surrounding shallow crust. At 105 Ma, a decrease to very slow cooling (nearly isothermal) (Fig. 3B) indicates prolonged residence in the upper crust for over 40 m.y. following cessation of Median batholith arc magmatism.

DISCUSSION

Our field observations indicate that Sisters shear zone contains all the elements of a continental extensional detachment fault system, including a footwall of variably mylonitic granitoids with localized brittle overprint, and a brittley deformed hanging wall of unfoliated granite and conglomerate (Fig. 2B). Brittle overprinting of ductile fabrics is consistent with exhumation of the footwall during deformation. Juxtaposition of mid-crustal plutonic (lower-plate) rocks against tilted sedimentary (upper-plate) rocks is typical of large-magnitude detachment faults such as those of the Basin and Range Province of the western United States (Wernicke, 1992).

An extensional setting for the shear zone is further supported by contrasting thermal histories from footwall and hanging-wall samples. The ^{40}Ar/^{39}Ar mica ages from footwall rocks indicate slow cooling from ca. 93 to 89 Ma. This interval was followed by a period of moderately rapid cooling (20–30 °C/m.y.) from ca. 89 to 82 Ma, as determined from K-feldspar thermal modeling (Fig. 3B), which is attributed to extensional exhumation along the detachment fault. At ca. 82 Ma, the cooling rate decreased substantially to nearly isothermal conditions and thermal equilibrium with the hanging wall (Fig. 3B). The hanging-wall K-feldspar indicates thermal equilibration with the surrounding upper crust ~25 m.y. earlier. From Figure 3B, it can be seen that the currently exposed footwall rocks were ~200 °C hotter than the hanging-wall rocks at 89 Ma. Assuming a pre-extensional geothermal gradient of 20–30 °C/km (Rothstein and Manning, 2003), the thermal histories reflect 7–10 km of crustal excision along the Sisters shear zone. Using these constraints and the dip angle of the ultracataclasite described previously (27°, assuming no rotation), a range of 15–22 km of slip is estimated along the detachment fault.

The transition to slow cooling observed in footwall K-feldspar at ca. 82 Ma corresponds with the age of the oldest seafloor (chron 33r, 83.0–79.1 Ma) along the southeast margin of the Campbell Plateau (Larter et al., 2002) and is consistent with the tectonic model of Sutherland and Hollis (2001). Therefore, the decrease in cooling rate may reflect the timing of transition from continental extension to lithosphere rupture and formation of the Pacific-Antarctic spreading ridge between the Campbell Plateau and West Antarctica.

The discovery of the Sisters shear zone has at least three important implications for southwest Pacific Cretaceous tectonics. First, the Sisters shear zone lies along strike from the fault-bounded northwest margin of the Great South Basin (Cook et al., 1999). Lineations in footwall rocks are coincident with the extension direction inferred for the basin based on dip directions of seismically identified normal faults, which indicates a major role for the Sisters shear zone in the formation of this large hydrocarbon-prospective basin. Second, the Sisters shear zone cuts across the trend of thickened arc crust of the Median Batholith (Tulloch and Kimbrough, 2003), which indicates that it is unlikely that gravitational collapse was the driving mechanism for Sisters shear zone extension (cf. Dewey, 1988; Rey et al., 2001). Third, ^{40}Ar/^{39}Ar thermochronometry data from the Sisters shear zone support a two-stage rifting model for the Gondwana Pacific margin (discussed next).

TWO-STAGE ZEALANDIA RIFTING MODEL

The timing of cooling recorded by K-feldspar of the Sisters shear zone (ca. 89–82 Ma) is younger than that in both the Ross Sea (ca. 100–92 Ma; Siddoway et al., 2004) and the Paparoa metamorphic core complex (ca. 92–88 Ma; Spell et al. 2000) (Fig. 4A). This discrepancy may be explained by a two-stage rift model that incorporates the model of detachment fault control on the formation of asymmetric continental margins of Lister et al. (1986). In this model, stage 1 (101–88 Ma) is asymmetric extension between a

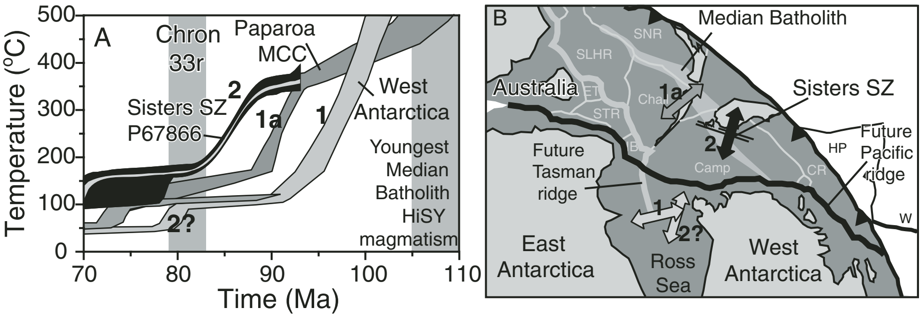

Figure 4. Two-stage rift model for breakup of Gondwana margin. A: Comparison with regional thermochronometry data from Western Province, New Zealand (Spell et al., 2000) and Marie Byrd Land, West Antarctica (Siddoway et al., 2004). Onset of footwall cooling occurs ~15 m.y. after final phase of Median batholith HiSY magmatism (Tulloch and Kimbrough, 2003), indicating tectonic origin rather than conductive cooling. B: Rigid plate reconstruction (ca. 95 Ma) of Gondwana margin—fragments of New Zealand represent the arc/forearc region (from Mortimer et al. 2005). Thermal histories in A correspond to numbered arrows in B representing two distinct stages of margin rifting: stage 1—northward propagation of Tasman Ridge (thick gray line); stage 2—Sisters shear zone (SZ) extension leading to opening of the Pacific-Antarctic Ridge (thick black line; see discussion). Abbreviations: Camp—Campbell Plateau; CR—Chatham Rise; HP—Hikurangi Plateau; W—Wishbone Ridge; Chall—Challenger Plateau; SLHR—South Lord Howe Rise; STR—South Tasman Rise; ET—East Tasman Rise; SNR—South Norfolk Ridge; IB—Iselin Bank; MCC—metamorphic core complex.

lower plate of Zealandia–West Antarctica and an upper plate of Australia–East Antarctica, resulting in formation of the Tasman Ridge (Tulloch and Kimbrough, 1989; Spell et al., 2000). Thermal histories determined for mylonite dredged from the Ross Sea (Siddoway et al., 2004) and the Paparoa footwall (Spell et al., 2000) would thus record the northward propagation of the Tasman rift zone (Fig. 4). Stage 2 (89–82 Ma) is extension between a lower plate of Zealandia and an upper plate of West Antarctica, producing the Pacific-Antarctic Ridge; the thermal history of the Sisters shear zone footwall records this event, and lineations there are subparallel to Pacific-Antarctic Ridge spreading, thus supporting a kinematic relationship. A second, short-lived interval of rapid cooling at ca. 80 Ma from West Antarctica (Fig. 4) may reflect a second stage of exhumation by rift flank uplift of the upper plate in proximity to the newly formed spreading ridge (see Sutherland and Hollis, 2001). This interpretation is consistent with rapid exhumation of a mid-crustal shear zone in the Fosdick Mountains that was subsequently tilted and cut by Late Cretaceous normal faults (Richard et al., 1994). In this two-stage rifting model, Zealandia represents the lower plate to two asymmetric rift systems, Australia and East Antarctica both represent the upper plates to an asymmetric rift, and West Antarctica changes from the lower plate of the Tasman rift to the upper plate of the Pacific-Antarctic rift. This model and the thermochronometry data presented herein are consistent with and support previous assertions that the separation of New Zealand from West Antarctica was the final stage of Gondwana breakup (Larter et al., 2002; Siddoway et al., 2004).

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