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Mid-Cretaceous ductile deformation on the Eastern Palmer Land Shear Zone, Antarctica, and implications for timing of Mesozoic terrane collision

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Abstract – Ar–Ar dating of high-strain ductile mylonites of the Eastern Palmer Land Shear Zone in the southern Antarctic Peninsula indicates that reverse movement on the shear zone occurred in late Early Cretaceous times (Albian), and not latest Jurassic times as previously supposed. The Eastern Palmer Land Shear Zone forms a major tectonic boundary, separating suspect arc terranes from rocks of Gondwana continental affinity. The dated mylonites are developed in Lower Jurassic plutonic rocks at Mount Sullivan, eastern Palmer Land, and form part of a zone of ductile reverse deformation up to 25 km wide. Biotite from a fine-grained mafic mylonite yields an Ar–Ar cooling age of 102.8 ± 3.3 Ma. Movement of this age on the Eastern Palmer Land Shear Zone is coeval with circum-Pacific deformation, possibly related to a mantle superplume event, and provides support for allochthonous-terrane models for the Antarctic Peninsula with accretion in post-Early Cretaceous times.

Keywords: Antarctic Peninsula, Gondwana, superplumes, orogeny, structural geology.

1. Introduction

The Eastern Palmer Land Shear Zone (Fig. 1) is a major tectonic boundary in the southern Antarctic Peninsula (Vaughan & Storey, 2000). It affected Late Palaeozoic and Mesozoic crystalline basement rocks and is associated with terrane accretion on the Gondwana margin. Vaughan & Storey (2000) associated the shear zone with deformation during the Palmer Land event (Kellogg & Rowley, 1989), a major compressional orogeny on the margins of the Gondwana supercontinent that was active during the main phase of Gondwana break-up. However, movement on the Eastern Palmer Land Shear Zone has never been directly dated. Previously, deformation on the Eastern Palmer Land Shear Zone was thought to have occurred some time between Early Jurassic (*c.* 199 Ma) and Early Cretaceous (*c.* 123 Ma) times (Storey, Vaughan & Millar, 1996), based on relationships between the shear zone and magmatic rocks. New Ar–Ar-based radiometric data presented in this paper show that the main phase of activity on the Eastern Palmer Land Shear Zone is mid-Cretaceous in age and occurred at *c.* 103 Ma.

2. Tectonic framework

Although traditionally viewed as a conventional magmatic arc (e.g. Suárez, 1976), recent discoveries suggest that the Antarctic Peninsula is composed of at least two suspect terranes in fault contact with para-autochthonous, continental, Gondwana margin rocks (Vaughan & Storey, 2000). Accretionary complex rocks of the Western Domain terrane (Fig. 1), and magmatic arc rocks of the Central Domain terrane (Fig. 1) may have docked with continental, shallow marine and volcanic rocks of the para-autochthonous Eastern Domain (Fig. 1) during the Palmer Land event. Western Domain rocks have similarities with Gondwana marginal accretionary complex rocks in New Zealand and southern South America. Permian to Cretaceous, microcontinental Central Domain rocks have strong similarities with rocks of the New Zealand Median Tectonic Zone, and the Coastal Cordillera of northern Chile (Vaughan & Storey, 2000). A large volume of structural data suggests oblique to orthogonal convergence between the Western and Central domains and the Gondwana margin during ductile to brittle–ductile movement along the Eastern Palmer Land Shear Zone (Vaughan & Storey, 2000). Based on this data, any docking of allochthonous terranes was probably dextral–oblique, with terrane arrival from the modern-day southwest.

3. Regional geology

Palmer Land event structure and timing were studied in eastern Palmer Land in the southern Antarctic

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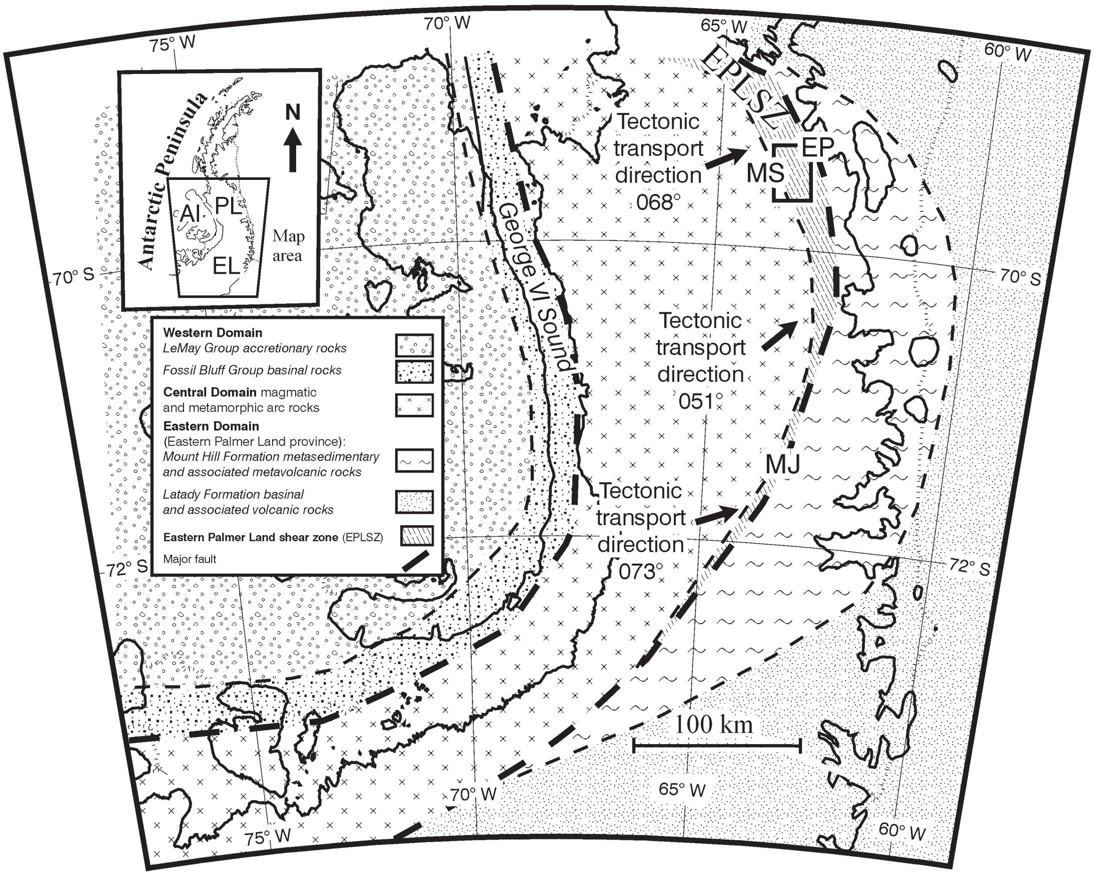

Figure 1. Map showing regional location of Mount Sullivan. AI – Alexander Island, EL – Ellsworth Land, EP – Engel Peaks, EPLSZ – Eastern Palmer Land Shear Zone, MJ – Mount Jackson, MS – Mount Sullivan, PL – Palmer Land. Box in upper right shows location of Figure 2.

Peninsula. In eastern Palmer Land (Fig. 1), the Eastern Palmer Land Shear Zone forms a major crustal boundary up to 25 km wide, which separates crystalline magmatic and metamorphic arc rocks of the Central Domain from low-grade metamorphosed sedimentary and volcanic rocks of the Eastern Domain (Vaughan & Storey, 2000). The Eastern Palmer Land Shear Zone is expressed as two main tectonic facies: (1) a broad, kilometre-wide zone of ductile LS-tectonite mylonite, and (2) a zone of polyphase tectonomagmatic breccias (Vaughan & Storey, 2000). The zone of ductile deformation of the Eastern Palmer Land Shear Zone narrows from approximately 25 km wide at Mount Sullivan to roughly 3 km wide at Mount Jackson, where the tectonomagmatic breccias are developed (Fig. 1; Vaughan & Storey, 2000). This paper presents the first precise age for ductile deformation on the Eastern Palmer Land Shear Zone, from cooling ages of biotite in mylonitized mafic plutonic rock.

3.a. Eastern Palmer Land Shear Zone in northeastern Palmer Land

The Eastern Palmer Land Shear Zone at Mount Sullivan (69° 40' S, 63° 47' W; Figs 1, 2) is a high-strain, ductile zone that deformed crystalline, metamorphic rocks, gabbroic to granitic plutons and metasedimentary rocks (e.g. Meneilly, 1988). The shear zone dips steeply west with an overthrust sense to the northeast (Vaughan & Storey, 2000). Deformation ranges from proto- to ultramylonite and pseudotachylyte, with major zones of breccia developed to the east at Engel Peaks (Meneilly, 1988; Fig. 1). Crystalline metamorphic rocks include layered, quartzofeldspathic gneiss, mafic, garnetiferous restitic gneiss, and migmatite. Plutonic rocks are commonly highly deformed, but include gabbro, porphyritic diorite, porphyritic granodiorite and granite.

Mafic to intermediate mylonite was sampled at Mount Sullivan (R.7170, Fig. 2), where the primary igneous rock types, listed above, intruded quartzofeldspathic and garnetiferous restitic gneiss. The igneous rocks form a heterogeneous assemblage, in many cases showing evidence of having mingled as liquid magma, passing laterally from one into the other over several metres. The degree of deformation ranges from proto- to ultramylonite.

3.a.1. Coarse-grained mafic to intermediate plutonic protoliths

Gabbro at Mount Sullivan is heterogeneous, ranging from coarse (1–2 cm) hornblendite, through medium-

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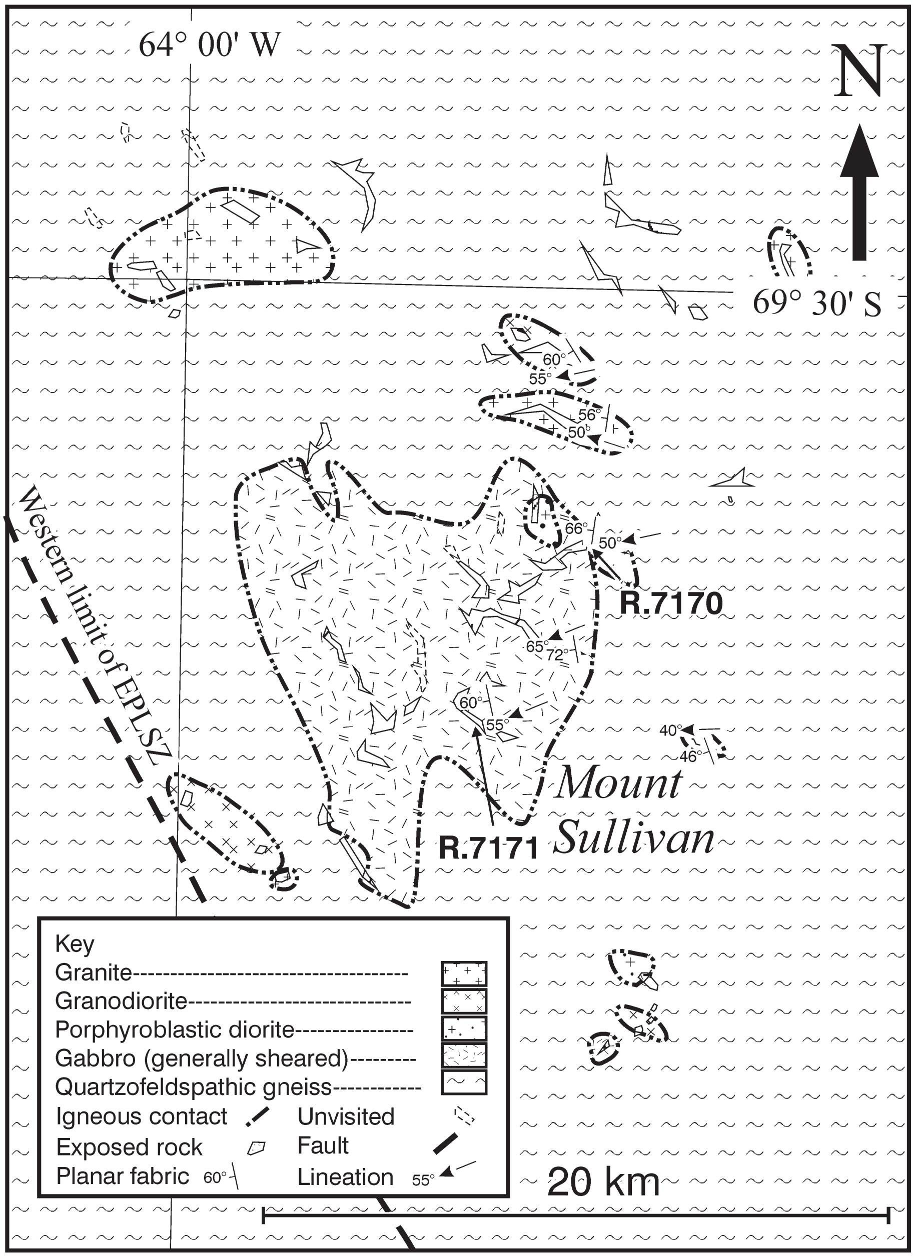

Figure 2. Sketch geology of Mount Sullivan showing localities mentioned in the text. EPLSZ – Eastern Palmer Land Shear Zone.

grained, hypidiomorphic types, to microgabbro, with some intermingling between medium-grained and microgabbroic types. Mineralogy includes hornblende, primary, magmatic biotite and plagioclase. Aplite dykes are sparse. Gabbro shows ambiguous, possibly liquid–liquid, contacts with porphyritic diorite, which resembles an altered or heteromorphic version of the gabbro.

Granodiorite is pale grey, and coarse-grained with 1–2 cm diameter, subspherical phenocrysts/porphyroblasts of concentrically zoned K-feldspar in a groundmass consisting of plagioclase, K-feldspar, fox-red biotite and hornblende. On a larger scale, granodiorite contains 3–5 cm long xenoliths of microdiorite with mingling textures, confirming an origin as droplets in liquid magma. In places, the intrusive contains irregular gabbro xenoliths, with reaction margins in some cases, and some textures suggest mingling of granodiorite and gabbro magma, indicating that both may have intruded synplutonically.

3.a.2. *Reverse shear zones*

Tectonic fabrics range from protomylonitic to ultramylonitic, and deformation occurred at up to amphibolite facies. The gabbro is heterogeneously sheared in zones up to 20 m wide. Mylonites consist of a domainal assemblage of sub-millimetric grains of hornblende, biotite and quartz, with minor muscovite; epidote forms millimetre-wide zones in some cases.

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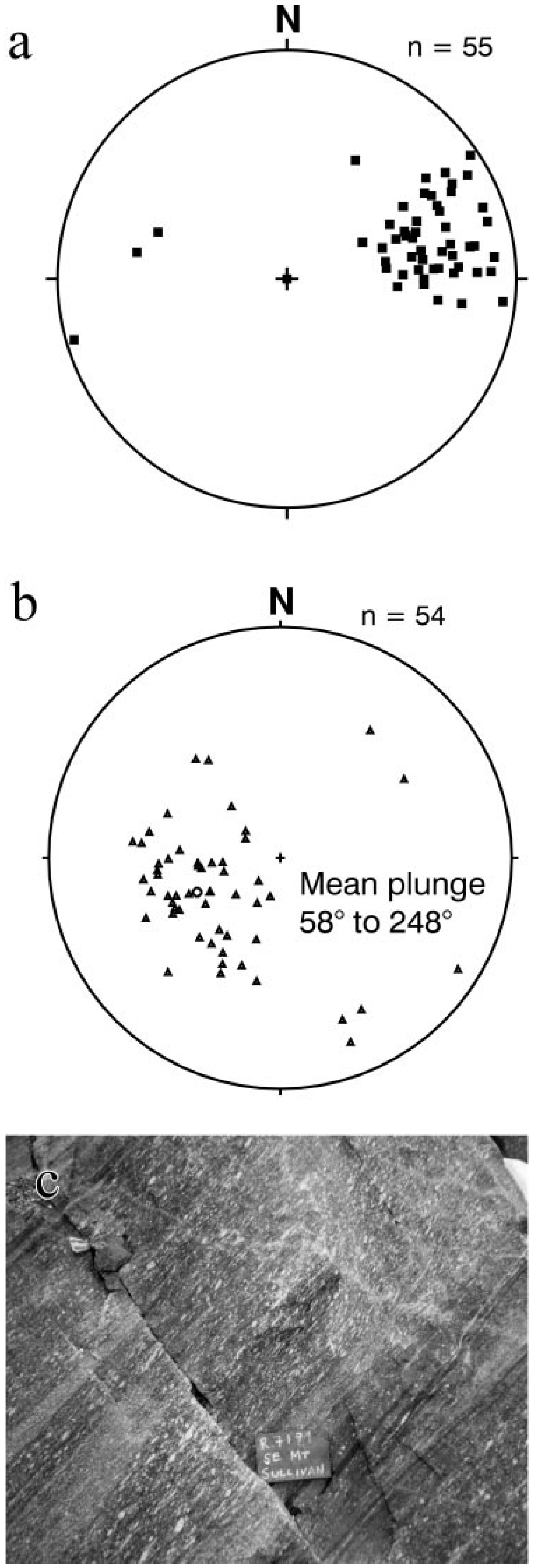

Figure 3. (a) Equal area lower hemisphere projection of contoured poles to mylonite foliation and (b) equal area lower hemisphere projection of mineral lineation, in Mount Sullivan rocks affected by the Eastern Palmer Land Shear Zone. (c) Foliated diorite from Mount Sullivan (R.7171, Fig. 2) with abundant σ- and δ-porphyroclasts (Passchier & Simpson, 1986) with asymmetries that indicate reverse shear (mylonite surfaces dip *c.* 35° west). Small chalkboard is 15 cm long.

Protomylonite to ultramylonite fabrics, with S-, L- and LS-tectonite geometries (Flinn, 1965), dip or plunge moderately to steeply southwest (Fig. 3a), and in S-tectonites a mineral lineation plunges steeply west to southwest (Fig. 3b). In thin section, mylonites show weak S–C fabrics (Simpson & Schmid, 1983); kinematic indicators in gabbro are ambiguous. Feldspar and biotite are deformed to sub-millimetric-scale rods in L-tectonite fabrics but show only weak asymmetry that suggests reverse shear. In porphyritic diorite, phenocrysts/porphyroblasts are deformed to σ- and δ-porphyroclast shapes (Passchier & Simpson, 1986) and the asymmetry of these, with the sense-of-curvature of associated S–C fabrics (Simpson & Schmid, 1983), gives good evidence of reverse shear during deformation (Fig. 3c) on surfaces that dip moderately to steeply southwest. Mingled granodiorite and gabbro are dragged with a dextral–reverse sense into high strain zones, with abundant σ- and δ-porphyroclasts (Passchier & Simpson, 1986) that indicate reverse shear on surfaces dipping moderately to steeply west. In granodiorite, biotite grain long-axes and boundaries define a non-fissile, planar fabric that forms the 'S' and 'C' surfaces of S–C mylonite. A biotite-defined, stretching lineation pitches steeply south; in thin section biotite shows well-developed biotite 'fish' textures (e.g. Kanaori, Kawakami & Yairi, 1991). K-feldspar phenocrysts/porphyroblasts have σ-porphyroclast shapes, with quartz and biotite tails. The asymmetry of these porphyroclasts and the sense of curvature of S–C fabrics are consistent with those in gabbro, and indicate deformation during bulk reverse shear with tectonic transport direction to the northeast on steeply W-dipping surfaces. Sheath-like or conical folds are also developed in mylonitic high-strain zones associated with dioritic or basaltic units within the main granodiorite.

4. Ar–Ar dating

A slab sample of mafic ultramylonite from locality R.7170 at the east side of Mount Sullivan (Fig. 2), consisting of a sub-millimetric assemblage of inclusion-free, elongate biotite and feldspar, with minor muscovite, was selected for dating (Table 1). The sample was washed in methanol and de-ionized water before being packed in aluminium foil and irradiated at the Ford reactor, University of Michigan. Upon return the slab was loaded into a laser port with a fused silica window. Spots were fused with a focused

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Table 1. Ar–Ar data for R.7170.12

J = 0.012	Sample	^{40}Ar/^{39}Ar	^{38}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar	^{40}Ar*/^{39}Ar	±	Age (Ma)[a]	±[a]
R.7170.12	1	11.49539	0.031953	3.546959	0.009553	8.672479	0.284425	*178.6115*	*5.641525*
R.7170.12	2	9.2341	0.026501	3.444822	0.013827	5.148087	0.081632	108.1449	1.745204
R.7170.12	3	8.631622	0.027419	3.170845	0.012679	4.88507	0.027415	102.7741	0.750878
R.7170.12	4	7.970437	0.029734	2.779705	0.01137	4.610544	0.057522	97.15119	1.271232
R.7170.12	5	7.562629	0.028288	1.699788	0.008091	5.17188	0.048654	108.63	1.123139
R.7170.12	6	7.838115	0.032055	2.097637	0.008649	5.282467	0.050024	110.8828	1.151651
R.7170.12	7	7.445033	0.029018	2.332897	0.008294	4.994135	0.027335	105.0031	0.756197
R.7170.12	8	7.547109	0.025286	1.633564	0.009776	4.658286	0.046232	98.13031	1.061375
R.7170.12	9	8.275724	0.026204	2.516692	0.012087	4.704135	0.039567	99.07011	0.94325
R.7170.12	10	8.198163	0.029179	2.928662	0.011695	4.742403	0.030049	99.85415	0.784063
Mean age (errors at 95 % confidence level)								102.8	3.3

[a] Data in italics are excluded from Figure 3.

beam from a Nd–YAG laser running at the fundamental wavelength of 1064 nm, using techniques described in Kelley (1995). Gas samples were getered for a minimum of five minutes and equilibrated into an MAP215-50 noble gas mass spectrometer with a Johnston multiplier. All argon peaks were scanned ten times and peak heights extrapolated back to the inlet time to allow for argon build-up and memory effects. The data, which are presented in Table 1 and plotted on Figure 4, were corrected for mass spectrometer discrimination and irradiation interference reactions. Ages calculated were based upon analyses of the GA1550 biotite standard (Renne *et al.* 1998). The sample is very fine grained and was analysed using single laser spots. Atmospheric contents were high for all analyses but there was little spread in either ^{36}Ar/^{40}Ar or ^{39}Ar/^{40}Ar ratio, and an isochron (109 ± 19 Ma; 2 sigma errors) yields high errors. Although one laser spot (Sample 1) yielded excess argon (see Table 1), the remaining points gave no indication of excess argon. The one data element is so removed from the others it is likely to represent a fluid inclusion contribution. A weighted mean of the remaining points yielded an age of age of 102.8 ± 3.3 Ma with MSWD of 20 (the quoted error is at the 95 % confidence level and has been enhanced using Student's t times the square root of the MSWD).

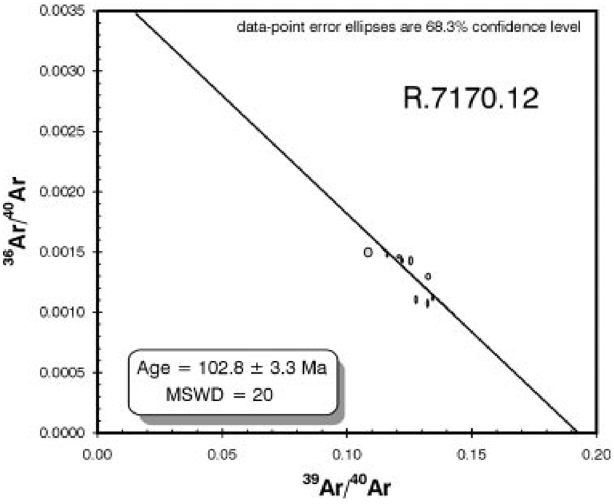

Figure 4. Plot of Ar–Ar data from hornblende in sample R.7170.12.

5. Discussion

Pankhurst (1983) dated granodiorite from Mount Sullivan at 178 ± 2 Ma using the Rb–Sr whole-rock method and interpreted this age as a magmatic cooling age. Given that no metamorphic events have been identified that post-date the phase of deformation described here, the new Ar–Ar laserprobe method age for mafic mylonite from Mount Sullivan most likely represents the cooling age of biotite after resetting during high-strain, high-temperature ductile shearing at *c.* 103 Ma. The shear zone rocks have not previously been directly dated, but a granophyre sheet, ductilely deformed and brecciated in a 1 km wide zone of reverse mylonite and complex breccias developed in rhyolitic and amygdaloidal basaltic rocks at Engel Peaks (Fig. 1), was dated at *c.* 113 Ma (Meneilly, 1988). This granophyre sheet places a lower age limit on Eastern Palmer Land Shear Zone deformation at Engel Peaks. The new age data presented here confirm a mid-Cretaceous age for shearing on the Eastern Palmer Land Shear Zone.

Vaughan & Storey (2000) interpreted the Eastern Palmer Land Shear Zone as a major collisional boundary between the arc rocks of the Central Domain terrane and para-autochthonous metasedimentary rocks of the Gondwana margin, and suggested that deformation and any terrane collision occurred in Late Jurassic or Early Cretaceous times; new dating of the age of folding suggests that deformation and any terrane collision occurred in late Early Cretaceous times (Vaughan, Pankhurst & Fanning, 2002). The new age data presented here provide increasing evidence that collision between the Central and Eastern domains could have occurred as late as Albian times, and for the first time link high-temperature ductile deformation with thin-skinned fold-and-thrust deformation of the Palmer Land event. Although the

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Central and Western domain terranes are currently merely suspect, the locations of the Central Domain and by association the Western Domain are now uncertain up to Albian times. This means that palaeogeographic interpretations based on palaeoclimatic evidence from pre-Albian rocks on Alexander Island and in the northern Antarctic Peninsula (e.g. Cantrill, 1998) may require some reassessment. Current interpretations based on leaf phenology, such as Falcon-Lang & Cantrill (2001), place Alexander Island (the Western Domain of Vaughan & Storey, 2000) at 75° S in Albian times. This may indeed be correct for Alexander Island as an allochthonous terrane, but may not reflect the palaeolatitude of the rest of West Gondwana at this time. Sea-floor reconstructions (e.g. Sutherland & Hollis, 2001) and structural data (Vaughan & Storey, 2000) indicate large-scale dextral shearing along the Gondwana margin that allows for potential movements of several thousand kilometres relative to the South Pole, of rocks that now preserve key environmental and latitude information.

The new age for deformation on the Eastern Palmer Land Shear Zone coincides with a major, Pacific-wide episode of deformation, possibly associated with the mid-Cretaceous impact of a mantle superplume in the area of what is the modern-day South Pacific (Vaughan, 1995), associated with a major plate reorganization (e.g. Sutherland & Hollis, 2001). This would have had the effect of uplifting and rejuvenating the sea-floor, reducing its thermal age and causing increased coupling between the overriding and subducting plate (Vaughan, 1995). Although the origin of the Palmer Land event is not known, one possibility is that the associated change in plate boundary forces caused orogenesis along the Gondwana margin. In support of this, the new age for Eastern Palmer Land Shear Zone movement is within error of a major phase of uplift and basin shoaling at *c.* 100 Ma on Alexander Island (Storey *et al.* 1996), and overlaps in age with ductile, W-directed thrusting with associated transfer faulting in western Palmer Land (Vaughan, Millar & Thistlewood, 1999). The age data presented here, and a new late Early Cretaceous age for the Palmer Land event in the southernmost Antarctic Peninsula (Vaughan, Pankhurst & Fanning, 2002), suggests that uplift on Alexander Island and deformation at Auriga Nunataks are also expressions of the Palmer Land event.

6. Conclusions

(1) High-strain ductile mylonite of the Eastern Palmer Land Shear Zone is developed in Early Jurassic gabbro at Mount Sullivan, eastern Palmer Land.

(2) Ar–Ar laserprobe dating of cooling ages for biotite in mafic mylonite suggests that high-temperature, reverse ductile shearing was active at 102.8 ± 3.3 Ma.

(3) Mid-Cretaceous deformation on the Eastern Palmer Land Shear Zone is coeval with circum-Pacific deformation that was possibly related to a superplume. If deformation on the shear zone occurred during terrane collisions, then such collisions on the Gondwana margin are later than previously assumed.

(4) The Eastern Palmer Land Shear Zone appears to be a deep-level, high temperature expression of deformation during the Palmer Land event.

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