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A tectonic model of the Antarctic Gondwana margin with implications for southeastern Australia: isotopic and geochemical evidence

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ABSTRACT

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Geochemical studies of Paleozoic granites in northern Victoria Land (NVL) and the central Transantarctic Mountains (CTM) are integrated with structural and lithologic studies into a model for the tectonic development of the Antarctic–southeast Australian Gondwana margin in late Precambrian–middle Paleozoic time. Isotopic data (Nd, Sr, O) are used to define crustal basement age boundaries and subduction polarity and thus help identify suspect terranes. In the CTM, three basement age-blocks are recognized: The outboard two provinces are inferred to be allochthonous, with accretion to the Gondwana margin occurring between ≈ 750 and ≈ 500 Ma. This tectonic scenario is inferred to apply also to NVL and southeastern Australia (SEA). In the CTM and NVL, chemical and isotopic polarity of ca. 500 Ma granitoids indicate a cratonward-dipping subduction zone. In NVL, terranes outboard of the belt of ca. 500 Ma granites contain Devonian (ca. 400 Ma) *I*-type granites with chemical and isotopic polarity opposed to that of the ca. 500 Ma granites. In the furthest outboard position, *S*-type granites emplaced at ca. 600 and 525 Ma occur with ca. 400 Ma granites and indicate the presence of early Proterozoic basement. This NVL terrane collage is allochthonous; it was assembled, intruded by Devonian granites, and then tectonically accreted to the Gondwana margin between latest Devonian and Permian time. Terrane correlations with SEA imply that much of the latter was accreted to the Gondwana margin after Devonian time. Other fragments of this allochthonous continental collage are probably in Marie Byrd Land (West Antarctica) and New Zealand (including the Campbell Plateau).

Introduction

Geochemical studies of Paleozoic granites in northern Victoria Land (NVL) and the central Transantarctic Mountains (CTM) provide information about crustal structure and the tectonic environment of batholith emplacement (Borg et al., 1987, 1990). Specifically, isotopic studies of granites define lower crustal lithologic/age provinces (referred to as "blocks" in this discussion to emphasize the distinction from terranes defined by traditional mapping) and give the polarity of subduction associated with the formation of the granitic batholiths. This information allows us to identify suspect terranes and thereby construct a revised model for the tectonic development of the Ross Sea segment of the Antarctic Gondwana margin during late Precambrian–middle Paleozoic time.

The model presented here is based on work in two parts of the Transantarctic Mountains (Fig. 1): (1) northern Victoria Land (Borg et al., 1987, and this paper) and (2) the central Transantarctic Mountains between the Nimrod glacier and the Gabbro Hills (Borg et al., 1990). Terrane correlations proposed by Stump et al. (1986) allow us to extend the model to southeastern Australia (SEA). We present below first the geologic and geochemical data relevant to tectonic interpretations and terrane correlations, and then the tectonic model and its implications. Major pre-Mesozoic tectonostratigraphic terranes of the Austral–Antarctic

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Gondwana margin are shown on an interpretive sketch map using the reconstruction of Lawver and Scotese (1987) as the base map (Fig. 2).

Summary of geologic and geochemical data

Northern Victoria Land

In NVL three terranes have been recognized from west to east: the Wilson Terrane (amphibolite-grade metamorphic rocks), the Bowers Terrane (Cambrian island-arc volcanics and sediments unconformably overlain by pre-Devonian quartzo-feldspathic sedimentary rocks), and the Robertson Bay Terrane (post Cambro-Ordovician turbidites) (Fig. 2). Geologic descriptions and tectonic models relevant to NVL are contained in Laird et al. (1982), Bradshaw and Laird (1983), Stump et al. (1983, 1986), Borg (1984), Weaver et al. (1984), Vetter et al. (1984), Bradshaw et al. (1985), Gibson and Wright (1985), Babcock et al. (1986), Borg et al. (1986, 1987), Wodzicki and Robert (1986), Borg and Stump (1987), Bradshaw (1987), Gibson (1987), Kleinschmidt and Tessensohn (1987), Kleinschmidt et al. (1987a, b) and Sheraton et al. (1987) among others. Two major spatially and temporally separate episodes of granitic magmatism are recorded in NVL. One is represented by the lower Paleozoic Granite Harbour Intrusive Complex (≈ 500 Ma) in the Wilson Terrane and the other is the Devonian Admiralty Intrusive Complex (≈ 400 ma) in the Bowers and Robertson Bay Terranes.

The significant aspect of the granitic rocks in NVL is the evidence they contain for the existence of a former ocean basin between what are now the Wilson and Bowers Terranes. This evidence is derived from the Nd and Sr isotopic compositions

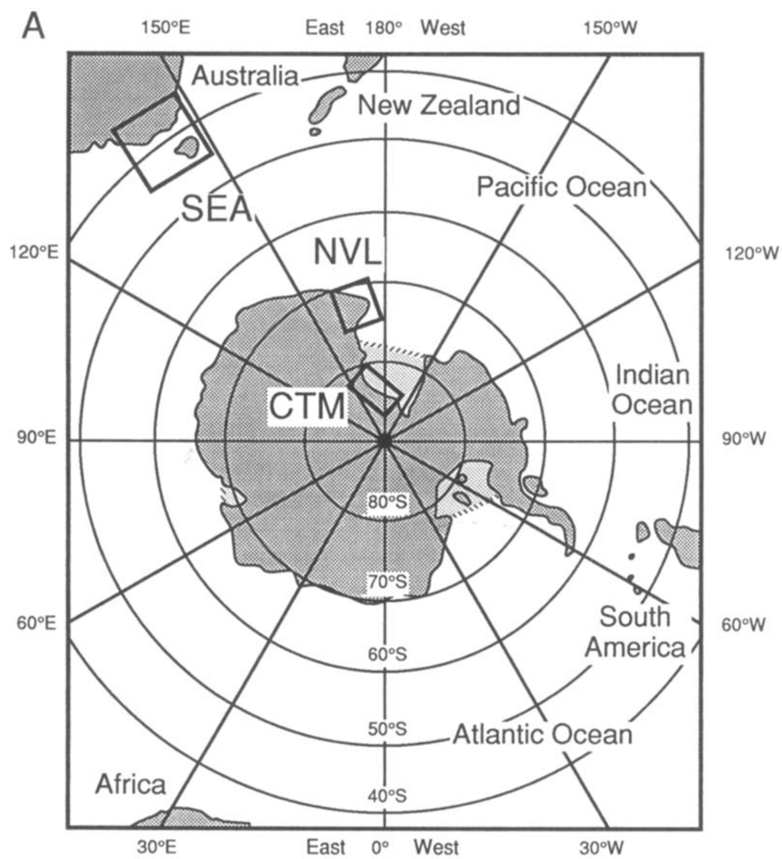


Fig. 1. (A) Antarctica and southeastern Australia showing locations of the transects discussed in this paper. *SEA* = southeastern Australia; *NVL* = northern Victoria Land; *CTM* = central Transantarctic Mountains. (B) Localities in Antarctica.

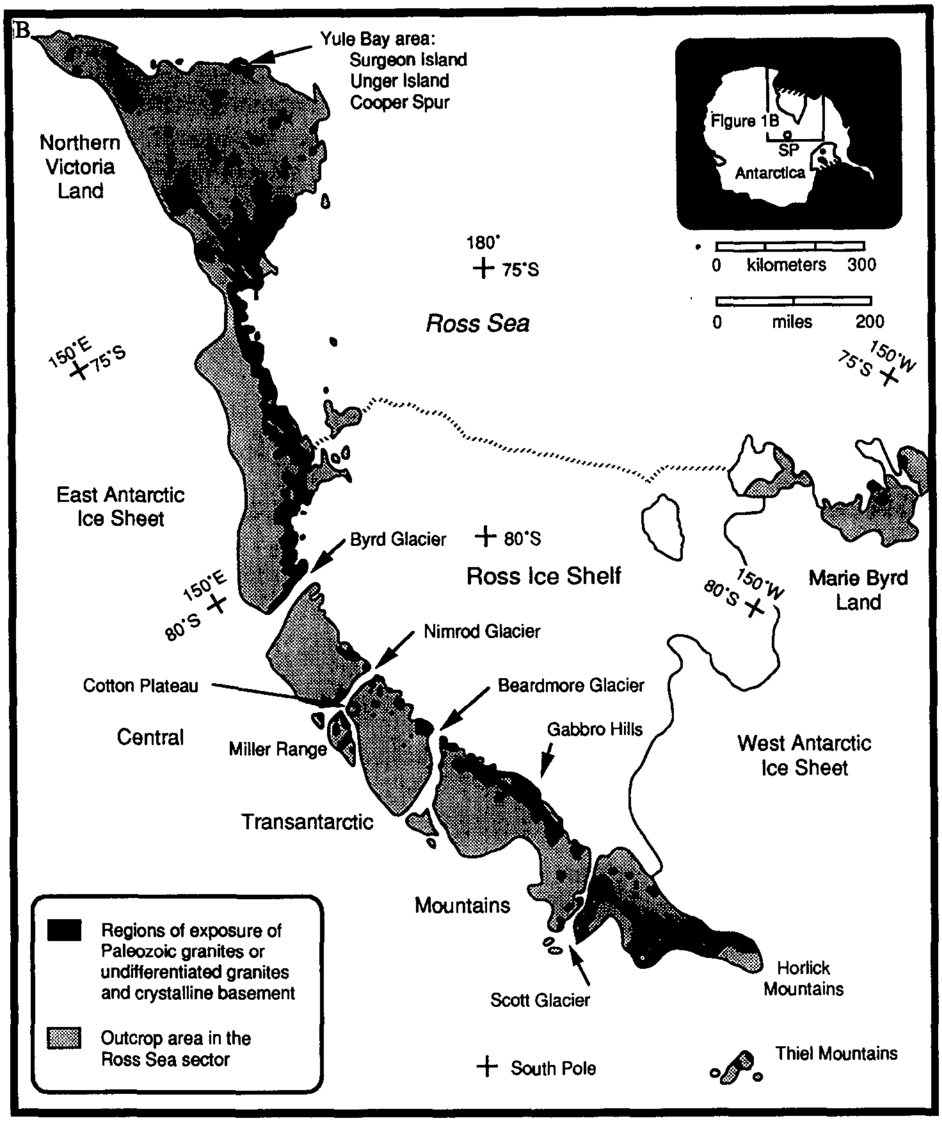


Fig. 1 (continued).

and the chemistry of the two suites of granites. These data indicate the age of the continental basement and give the polarity of the subduction zone associated with each granite suite (Table 1 and Fig. 3). The Nd isotopic compositions of the Granite Harbour Intrusive Complex indicate that the lower crust of the Wilson Terrane is composed of Proterozoic (ca. 2.0 Ga) rocks. The compositional polarity of the Granite Harbour Intrusive Complex in the Wilson Terrane reflects westward subduction beneath the East Antarctic Craton (Borg, 1984; Borg et al., 1987). In contrast, the compositional polarity in the Admiralty Intrusive Complex reflects northeastward subduction, forcing the conclusion that the crustal block represented by the Bowers Terrane + Robertson Bay Terrane is allochthonous (Borg et al., 1987; Borg and Stump, 1987).

Although these inferences are based on geographical isotopic and chemical patterns in the granitic rocks, other observations support them. For example, in the Wilson Terrane the Precambrian granite complex in the Daniels Range (Sheraton et al., 1987) corroborates the inference of old crust from the isotopic studies. The interpretation of westward subduction beneath the

Wilson Terrane in Cambro-Ordovician time is supported by the distribution of metamorphic provinces which resembles a paired metamorphic belt with craton to the west (Grew et al., 1984) and by the presence of metamorphosed mafic and ultramafic rocks on the eastern edge of the Wilson Terrane, which are inferred to be remnants of a subducted oceanic plate (Kleinschmidt et al., 1987b). Also, the interpretation of northeastward subduction associated with the Admiralty Intru-

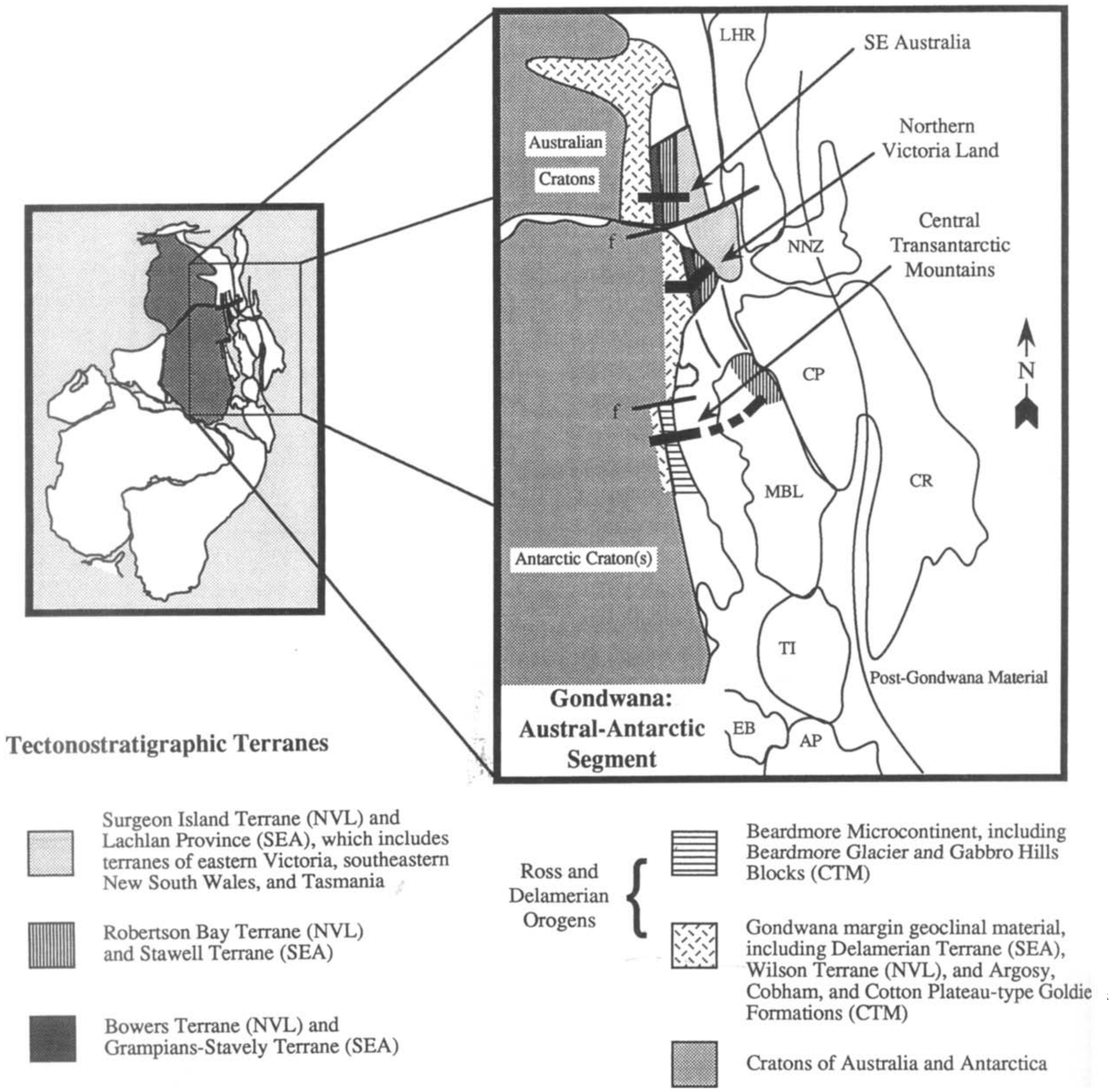


Fig. 2. Tectonostratigraphic terranes of the Austral–Antarctic segment of Gondwana. The reconstruction is from Lawver and Scotese (1987) with geology based on Stump et al. (1986) and Borg et al. (1987, 1990). The reassembly of Australia and Antarctica is essentially the same as that of Sproll and Dietz (1969). Modifications to this configuration proposed by Stump et al. (1986) would produce a tighter fit of marginal terranes but have not been included here so that the Antarctic and Australian elements can be more easily distinguished. For convenience of discussion, north has been arbitrarily chosen to be toward the top of the page. Continental fragments: *AP* = Antarctica Peninsula; *CP* = Campbell Plateau; *CR* = Chatham Rise (including South Island, New Zealand); *EB* = Ellsworth Block; *LHR* = Lord Howe Rise; *MBL* = Marie Byrd Land; *NNZ* = North Island, New Zealand; *TI* = Thurston Island.

TABLE 1

Rb–Sr and Sm–Nd concentrations and isotopic ratios for granites of Surgeon Island and Cooper Spur

Locality	Sample No.	[Rb]	[Sr]	[Sm]	[Nd]	$^{87}Rb/^{86}Sr$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd_{(0)}$	$\epsilon_{Nd}(0)$	$\epsilon_{Nd}(t)$	Nd Model Age	$^{87}Sr/^{86}Sr_{(0)}$	$^{87}Sr/^{86}Sr_{(t)}$	$\epsilon_{Sr}(t)$
Surgeon Island pluton (≈ 600 Ma)														
Surgeon Island	AL 1965	253.79	122.18	8.92	45.78	6.0734 (±24)	0.1178 (±1)	0.511037 (±21)	−15.61	−9.57	1.99	0.81093 (±3)	0.7590	783.9
Surgeon Island	AL 1968	183.20	123.28	6.67	35.87	3.9799 (±14)	0.1125 (±1)	0.510986 (±23)	−16.61	−10.15	2.03	0.78760 (±2)	0.7536	707.0
Cooper Spur pluton (≈ 525 Ma)														
Cooper Spur	AL 1975	167.37	165.61	7.53	40.46	2.9250 (±19)	0.1126 (±1)	0.511245 (±23)	−11.55	−5.90	1.69	0.73437 (±3)	0.7093	122.2

(1) See Borg et al. (1990) for analytical procedures. Concentrations are in ppm. Mass spectrometric procedures are given by DePaolo (1981). $^{143}Nd/^{144}Nd$ normalized to $^{146}Nd/^{142}Nd = 0.63613$. $^{87}Sr/^{86}Sr$ normalized to $^{86}Sr/^{88}Sr = 0.1194$.

(2) Epsilon notation follows DePaolo and Wasserburg (1979). ϵ_{Nd} is calculated with respect to a chondritic reservoir with present $^{143}Nd/^{144}Nd = 0.511836$ and $^{147}Sm/^{144}Nd = 0.1967$. $\lambda_{Sm} = 6.54 \times 10^{-12}$ yr^{-1}. ϵ_{Sr} is calculated with respect to a uniform reservoir with present $^{87}Sr/^{86}Sr = 0.7045$ and $^{87}Rb/^{86}Sr = 0.0827$. $\lambda_{Rb} = 1.42 \times 10^{-11}$ yr^{-1}. $\epsilon_{Nd}(t)$, $\epsilon_{Sr}(t)$, and $^{87}Sr/^{86}Sr_{(t)}$ are the compositions calculated at the reported crystallization ages, whereas $^{143}Nd/^{144}Nd_{(0)}$, $\epsilon_{Nd}(0)$, and $^{87}Sr/^{86}Sr_{(0)}$ are the measured compositions.

(3) Model ages are calculated relative to a depleted mantle model (ϵ_{Nd} [DM] = 8.6–1.91T; T = agein Gyr). Because these samples are granites, model ages were calculated from the initial composition using an Sm/Nd ratio which is dependent on crustal age (initial ϵ_{Nd}). See DePaolo (1988) and Borg et al. (1990).

(4) The tabulated uncertainty in the isotopic ratios is the 2σ error from the ratio measurement and pertains to the last digit or digits of the respective ratio.

(5) Uncertainty in the parent–daughter ratios was estimated from measured concentrations and respective 2σ uncertainties in the following equation: ([±2σ parent]/[parent]+[±2σ daughter]/[daughter])/(1-[±2σ daughter]/[daughter])∗[parent isotope]/[daughter isotope].

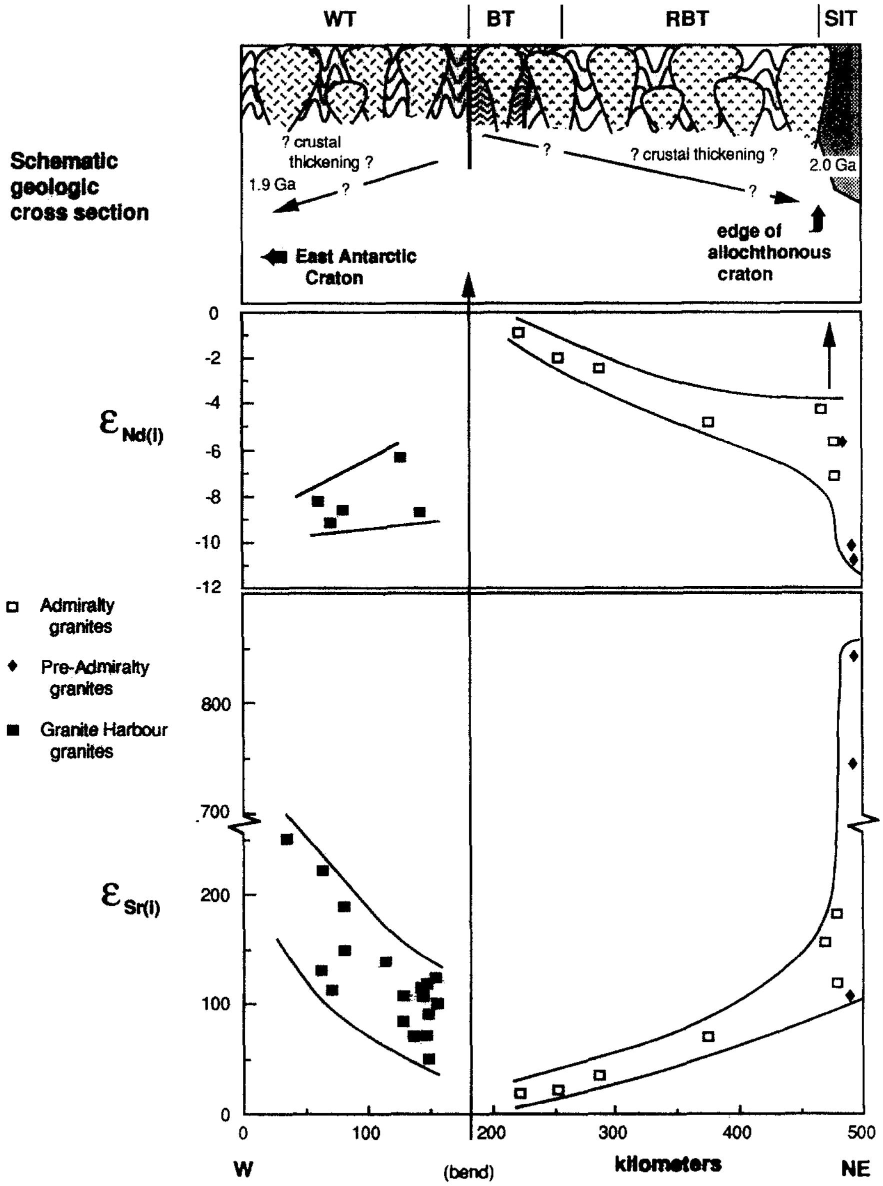


Fig. 3. Initial ϵ_{Nd} and ϵ_{Sr} versus position along the NVL transect of the Granite Harbour Intrusive Complex (calculated at 500 Ma), the Admiralty Intrusive Complex (calculated at 400 Ma), and the pre-Admiralty granites at Surgeon Island (calculated at 600 Ma) and Cooper Spur (calculated at 525 Ma). This diagram emphasizes the temporal and spatial separation of the Granite Harbour and Admiralty Intrusive Complexes and their correlation with metamorphic terranes. Breaks in the isotopic patterns indicate changes in lower crustal structure. The isotopic trends of the Granite Harbour and Admiralty Intrusive Complexes indicate polarity of subduction associated with each batholithic suite: westward subduction beneath the Wilson Terrane (ca. 1.9 Ga continental basement based on Sm–Nd model ages) at ca. 500 Ma for the former and northeastward subduction at ca. 400 Ma beneath the Bowers, Robertson Bay, and Surgeon Island Terranes (ca. 2.0 Ga continental basement based on Sm–Nd model age) in the latter. The boundary between each of these plutonic suites and the opposite polarity indicate a suture between the Wilson Terrane and the Bowers Terrane. The continuity of compositions across the Bowers–Robertson Bay Terrane boundary indicates lower crustal continuum. The isotopic shift at the boundary between the Robertson Bay and Surgeon Island Terranes marks a change in the lower crust which may be another suture. The Bowers, Robertson Bay, and Surgeon Island Terranes were assembled prior to emplacement of the Admiralty granites and accretion of this terrane collage to the Gondwana margin occurred after the Devonian. *WT* = Wilson Terrane; *BT* = Bowers Terrane; *RBT* = Robertson Bay Terrane; *ST* = Surgeon Island Terrane. Data are from Table 1 and Borg et al. (1987). Diagram is modified from Borg et al. (1987, fig. 11).

sive Complex and the allochthonous nature of the Bowers Terrane + Robertson Bay Terrane is supported, albeit indirectly, by the presence of two granitic plutons in the northeastern part of NVL that are older than the Admiralty Intrusive Complex: the Cooper Spur pluton (ca. 525 Ma) and the Surgeon Island pluton (ca. 600 Ma) (Vetter et al., 1984). These older granites establish the presence of Precambrian crust in northeastern NVL, as was predicted from the isotopic and chemical polarity of the Admiralty granites (Borg, 1984; Borg et al., 1987).

The northeastern part of NVL, northeast of the Robertson Bay Terrane, is here considered as a separate tectonostratigraphic terrane—the Surgeon Island Terrane. The granite crystallization ages of 525 and 600 Ma (Vetter et al., 1984) require this terrane to be older than the Cambro-Ordovician turbidites that are the oldest rocks of the Robertson Bay Terrane. One of the two older granites, the Surgeon Island pluton, has a peraluminous (*S*-type) chemical composition (Vetter et al., 1984) with an initial ϵ_{Nd} value that indicates derivation from Precambrian basement with a Sm–Nd model age of 2.0 Ga (Table 1 and Fig. 4). This age is in accord with the isotopic patterns in the Admiralty Intrusive Complex (Figs. 3 and 4) which indicate that these granites formed by mixing of mantle-derived magmas with ≈ 2 Ga crustal rocks. We infer, therefore, that the Bowers, Robertson Bay, and Surgeon Island Terranes were contiguous at the time of formation of the Admiralty Intrusive Complex, and that the Admiralty Intrusive Complex originated in association with northeastward subduction beneath a Proterozoic-age continental block. The Surgeon Island Terrane represents part of this Proterozoic continent and the Bowers and Robertson Bay Terranes represent material accreted to this continent between early Ordovician and Devonian time (cf. Borg and Stump, 1987).

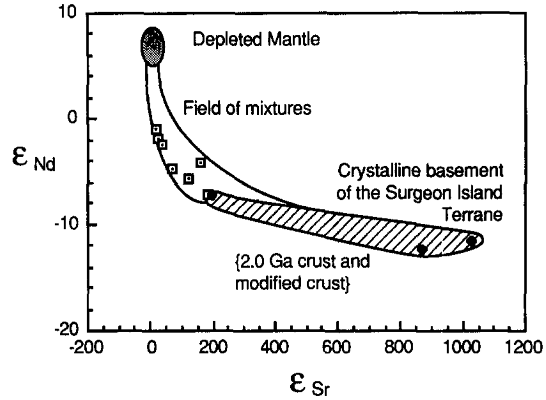
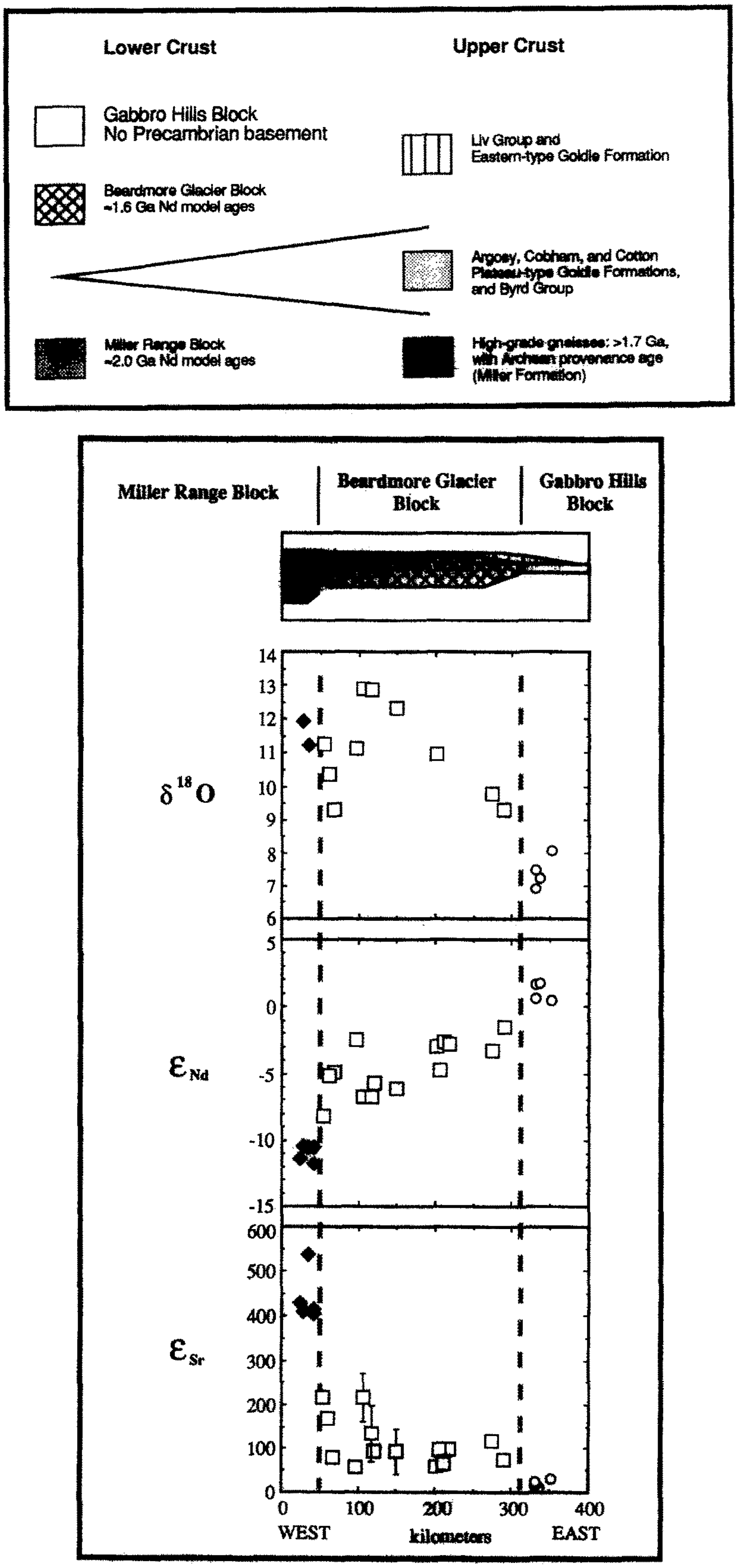


Fig. 4. ϵ_{Nd} versus ϵ_{Sr} for the Admiralty Intrusive Complex (□) and the older granites of the Surgeon Island Terrane (Cooper Spur and Surgeon Island plutons, ◆) calculated at 400 Ma. The Surgeon Island Terrane has crystalline basement with $T_{DM}^{Nd} \approx 2.0$ Ga. Prior to 400 Ma, this crust was modified by granite production at ≈ 600 Ma and ≈ 525 Ma. The diagonally shaded field shows the composition of the crustal basement of the Surgeon Island Terrane expected at 400 Ma, when plutons of the Admiralty Intrusive Complex formed. The data are compatible with formation of the Admiralty granites by mixing of mantle-derived magmas with Surgeon Island Terrane basement. Data from Table 1 and Borg et al. (1987).

Central Transantarctic Mountains

From west to east, the basement of the central Transantarctic Mountains consists of the margin of the East Antarctic Craton and younger accreted materials, all of which were intruded by ca. 500 Ma plutons (Figs. 2 and 5) (Borg et al., 1990). The Miller Range Block represents the East Antarctic Craton in this region and contains both Proterozoic and Archean crystalline rocks. The lower crust is inferred to be Proterozoic (ca. 2 Ga) based on Nd isotopic compositions of the ca. 500 Ma granites (Borg et al., 1990). High-grade metamorphic rocks of the Miller Formation comprise the upper plate of a low-angle thrust system rooted to the west (Grindley, 1972; Goodge et al., 1989). The earliest recorded event is deposition of sediments and volcanics which would become the high-grade gneisses and schists of the Miller Formation. Sm–Nd model provenance ages of ca. 2.8 Ga (Borg et al., 1990) and a U–Pb date on detrital zircon of ca. 3.0 Ga (Goodge et al., 1989) suggest a uniformly, and perhaps single, Archean sedimentary source. It is inferred that these sediments accumulated at the margin of an Archean craton based on the absence of Archean rocks outboard in Gondwana reconstructions and from the presence of the 2.0 Ga basement province at the continental fringe. At ≈ 1.7 Ga, the Miller For-



Lower Crust
Upper Crust
Gabbro Hills Block
No Precambrian basement
Beardmore Glacier Block
~1.6 Ga Nd model ages
Miller Range Block
~2.0 Ga Nd model ages
Liv Group and
Eastern-type Goldie Formation
Argosy, Cobham, and Cotton
Plateau-type Goldie Formations,
and Byrd Group
High-grade gneisses: >1.7 Ga,
with Archean provenance age
(Miller Formation)
Miller Range Block
Beardmore Glacier Block
Gabbro Hills Block
$\delta^{18}O$
ε_{Nd}
ε_{Sr}
0
100
200
300
400
WEST
kilometers
EAST

mation was intruded by a granodiorite which has yielded a ca. 2.7 Ga Sm–Nd model age (Borg et al., 1990). The times of deposition and first deformation of the Miller Formation are thus constrained only between 2.8 and 1.7 Ga. Shear fabrics in the Miller Formation and the granodiorite (*s–c* fabrics and mineral lineations; Goodge et al., 1989) indicate eastward overthrusting after 1.7 Ga and before emplacement of the ca. 500 Ma granites. To the east, the ca. 2.0 Ga basement of the Miller Range Block is bordered by a region of younger (ca. 1.6 Ga) Proterozoic basement which we have named the Beardmore Glacier Block. This lower crustal province is delineated on the basis of the Nd, Sr, and O isotopic compositions of its ca. 500 Ma granitoids. Metamorphic rocks associated with this basement province are lower greenschist facies turbidites, the eastern-type Goldie Formation of Borg et al. (1990). Outboard of the Beardmore Glacier Block is the Gabbro Hills Block where there is no isotopic evidence for Precambrian basement in the ca. 500 Ma granites. Metamorphic rocks in this region include the eastern-type Goldie Formation and the Liv Group.

The tectonic significance of the basement blocks of the central Transantarctic Mountains, as delineated by isotopic data, is provided by structural, lithologic, and isotopic data from older metasedimentary and metaigneous rocks. Precambrian metamorphic rocks now at the boundary between the Miller Range Block and the Beardmore Glacier Block, including the Argosy Formation (Sm–Nd provenance age of 2.7 Ga), the Cobham Formation, and the Cotton Plateau-type Goldie Formation (which includes basalt and gabbro (Stump et al., 1988) that have oceanic Nd isotopic signatures), are inferred to have been deposited on oceanic crust at the edge of the East Antarctic Craton at about 750 Ma (Borg et al., 1990). This indicates that the boundary between the Miller Range and Beardmore Glacier Blocks is a suture (Fig. 2 and 5). Furthermore, Nd isotopic compositions of turbidites of the Beardmore Glacier Block (eastern-type Goldie Formation) indicate that they were not derived from the local Antarctic craton (Borg et al., 1990). It is therefore inferred that the Beardmore Glacier Block was part of a different continent or attached to a different segment of the Gondwana margin at the time of deposition of the turbidites.

Isotopic data from the granitoids further imply that the Beardmore Glacier Block was sutured to both the Miller Range Block and the Gabbro Hills Block before 500 Ma. The former inference comes from the observation that the 500 Ma granites that intrude the oceanic assemblage at the Miller Range Block–Beardmore Glacier Block boundary are derived from underlying Precambrian basement rocks. Thus, the oceanic sedimentary and volcanic rocks were obducted or otherwise squeezed up between the basement blocks prior to 500 Ma. This structural juxtapositioning was presumably associated with docking of the Beardmore Glacier Block. The latter inference stems from the observation that the Gabbro Hills and Beardmore Glacier Blocks in combination show a coherent pattern of isotopic variation in the 500 Ma granitoids. We infer that these two blocks were joined in their present configuration and together comprise the Beardmore Microcontinent, which was accreted to the Gondwana margin prior to 500 Ma.

Further constraints on timing of accretion of the Beardmore Microcontinent are derived from

Fig. 5. Lower crustal provinces in the CTM defined by ca. 500 Ma granites. Nd, Sr, and O isotopic compositions of the ca. 500 Ma granites in the CTM allow the delineation of three basement provinces which correspond to differences in metamorphic rocks at the surface: The Miller Range Block has ≈ 2.0 Ga lower crust and a veneer of high-grade gneisses of Archean provenance. The Beardmore Glacier Block has ≈ 1.6 Ga lower crust with folded lower greenschist facies turbidites (eastern-type Goldie Formation) in the upper crust. The Gabbro Hills Block had no Precambrian basement at 500 Ma. Metamorphic rocks (Argosy, Cobham, and Cotton Plateau-type Goldie Formations) which occur at the boundary between the Miller Range Block and the Beardmore Glacier Block were squeezed up when the latter block was accreted to the Gondwana margin. Data from Borg et al. (1990). ◆ peraluminous granodiorite to granite; □ metaluminous to slightly peraluminous granodiorite to granite, occasional diorite; ○ gabbro, diorite, tonalite, and metaluminous granodiorite.

structural relationships between metamorphic rocks along the boundary between the Miller Range and Beardmore Glacier Blocks—specifically the Cotton Plateau-type Goldie Formation and the unconformably overlying lower Cambrian ($\approx$ 550 Ma) shelf limestones of the Byrd Group. The Cotton Plateau-type Goldie Formation records two phases of folding: the first is the Beardmore Orogeny and is represented by recumbent east vergent folds and the second is the Ross Orogeny and is represented by open upright to slightly southwest vergent folds (Edgerton, 1987; Stump et al., 1988). The Byrd Group along with all other rocks intruded by the ca. 500 Ma granites display open upright folds attributed to the Ross Orogeny. Because the early east vergent folds are restricted to the rocks along the boundary of the Miller Range and Beardmore Glacier Blocks and because a continental shelf environment for deposition of the Byrd Group resulted from the early deformation, we infer that the Beardmore Orogeny is associated with accretion of the Beardmore Microcontinent. This implies that accretion occurred between 750 and 550 Ma.

The distribution of lower crustal provinces in the central Transantarctic Mountains and the isotopic polarity of the ca. 500 Ma granitic rocks in the eastern part of the region (Fig. 5) are compatible with the interpretation that the magmas were associated with westward subduction during Cambro-Ordovician time (Borg et al., 1990).

Southeastern Australia

Three pre-Devonian terranes of southeastern Australia bear strong resemblances to those of Antarctica (Stump et al., 1986). The westernmost, the Delamerian Terrane in South Australia and western Victoria (Fig. 2) correlates with the Wilson Terrane of NVL. The Delamerian Terrane contains late Precambrian and early Paleozoic geoclinal sediments deposited on the margin of the Proterozoic Australian craton; these sedimentary rocks are intruded by Cambro-Ordovician granites. Immediately to the east is the Grampians–Stavely Terrane, which correlates with the Bowers Terrane in NVL. It contains a middle(?) Cambrian volcanic arc and associated marine sediments unconformably overlain by quartz-rich continentally derived sediments of late Cambrian or Ordovician age. This volcanic and sedimentary package is intruded by Devonian *I*-type granitoids. Further east, in central Victoria, the Stawell Terrane correlates with the Robertson Bay Terrane of NVL. This terrane is composed of quartzose, turbiditic graywacke and shale intruded by Devonian *I*-type granitoids. East of the Stawell Terrane, in central Victoria, are the Bendigo and Melbourne Terranes (Stump et al., 1986) which are here grouped with other terranes of the Lachlan Fold Belt of eastern Victoria and southeastern New South Wales (e.g., Scheibner, 1985, fig. 3; Leitch and Scheibner, 1987) into the Lachlan province. We correlate this province with the Surgeon Island Terrane of NVL. The Lachlan province is dominated by a variety of Ordovician–Devonian sedimentary rocks intruded by Silurian and Devonian granitoids. Sr and Nd isotopic data for granites of the Lachlan province indicate the presence of ca. 1.8–1.9 Ga basement (data from McCulloch and Chappell, 1982; model ages recalculated by the method described in Borg et al., 1990) west of the line that separates the *I*-type granite terrane from the *S*-type granite terrane (e.g. White et al., 1976) in southeastern New South Wales.

A feature of the Lachlan province that is not represented in NVL is the Cambrian Heathcote greenstone belt (cf. Scheibner, 1985, fig. 5; Stump et al., 1986) which occurs in the western Lachlan province near the boundary with the Stawell Terrane. On the basis of Sr and Nd isotopic data and trace element chemistry, these rocks are interpreted to represent a Cambrian oceanic island arc (Nelson et al., 1984). Thus, there appears to be an additional suture within SEA that is not known in NVL.

Two terranes in Tasmania can also be correlated with parts of the Lachlan province (Stump et al., 1986). Taswegia, occupying the western two thirds of the island, contains Cambrian–Devonian sedimentary and volcanic rocks that were deposited on Precambrian basement and later intruded by Devonian–Carboniferous granites. The Bassian Terrane, in the northeastern third of Tasmania, contains Ordovician–Devonian graywacke and shale that were also intruded by Devonian–Carboniferous granites (cf. Stump et al., 1986; Scheibner, 1985).

Summary of terrane correlations

Figure 6 shows terrane correlations and interpretive cross sections for Australia, northern Victoria Land, and the central Transantarctic Mountains. Terrane correlations between Australia and Antarctica are modified from Stump et al. (1986). The correlations between terranes, from north to south, follow partly from the fit of the continents (Fig. 2) and partly from the similarity of the geology, particularly the age of the sedimentary rocks and the age and character of the granitic rocks as described above.

The western portions of all three regions represent the eastern margin of a large Precambrian continent that included Proterozoic and Archean cratonic blocks of East Antarctica and Australia. Isotopic data suggest that most of the Precambrian rocks near the margin of this superconti-

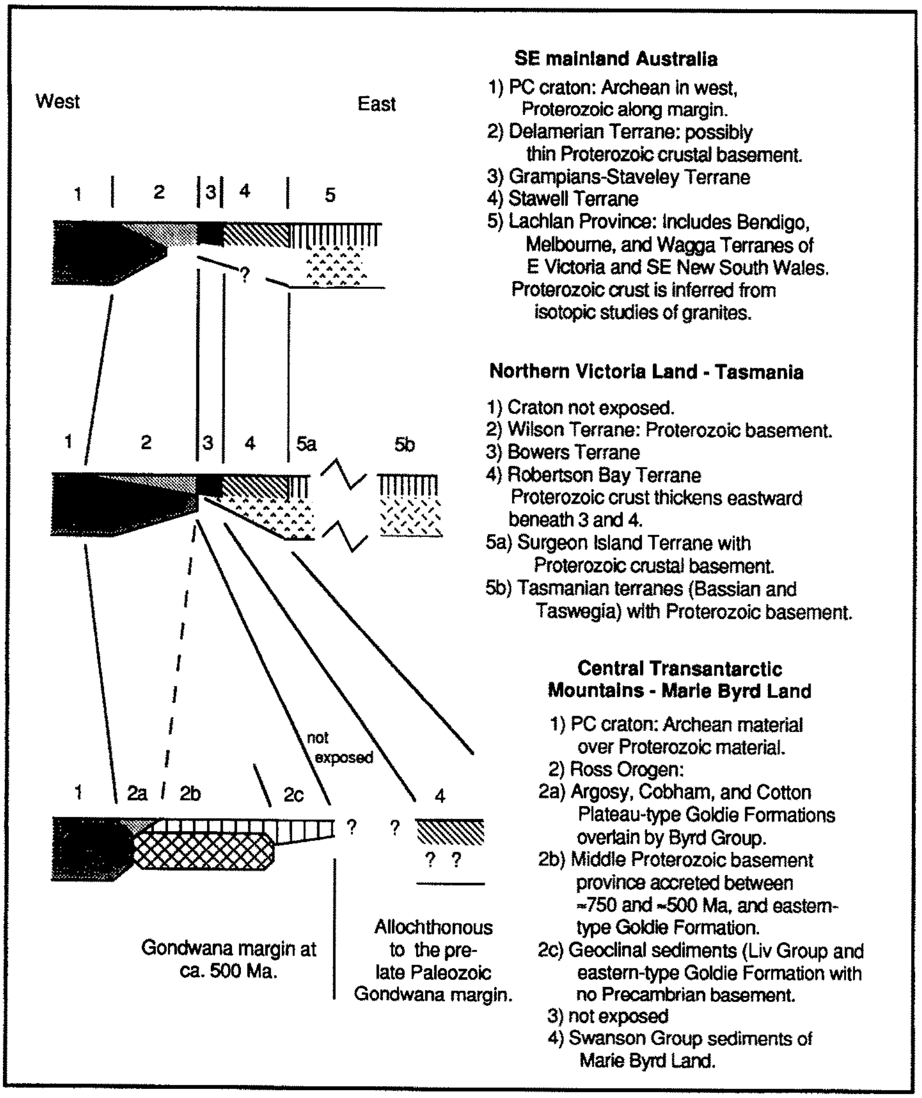


Fig. 6. Terrane correlation and crustal structure diagram. Pre-batholithic crustal structure inferred for three sections of the Paleo-Pacific margin of Gondwana. Locations of these transects (SEA, NVL, CTM) are shown in Fig. 2. For segments 1 and 2, granites were emplaced at ≈ 500 Ma. For segments 3 and 4, granites were emplaced at ≈ 400 Ma. Segment 5 contains late Preambrian (?), Cambrian (?), Silurian and Devonian granites.

nent have ages near 1.8–2.0 Ga (McCulloch, 1987; Borg et al., 1987, 1990) and are consistent with the reconstruction shown in Fig. 2. The primary geologic basis for correlation along this continental margin is the existence of upper Precambrian to lower Cambrian sedimentary sequences intruded by Cambro-Ordovician granitic batholiths—the Delamerian and Ross Orogenic Belts (Fig. 6, Segments 1 and 2).

The remaining eastern parts of each area contain rock sequences that developed at the western margin of a separate continent (Segments 3, 4, and 5 in Fig. 6). The existence of a suture representing the location of former ocean floor between segments 2 and 3 in Fig. 6 is based mainly on the geographical variations of isotopic and chemical compositions of granitic rocks in NVL. The former existence of ocean floor at this position in the east–west transect is confirmed to the south by the oceanic character of the easternmost granitic rocks in the CTM (Fig. 5) (Borg et al., 1990). The correlations of Segments 3 and 4 between NVL and SEA are based on the presence in each of Devonian granitic plutons intruding early Paleozoic sedimentary and volcanic rocks (Stump et al., 1986). This correlation, and the inference that a Precambrian continental craton lies to the east, are confirmed by the geochemical evidence in granitic rocks for Precambrian basement of about the same age (ca. 1.8–2.0 Ga) in both the Surgeon Island Terrane of NVL and the Lachlan province of SEA. Other parts of this Precambrian continent may be present today in Tasmania, Marie Byrd Land, New Zealand, and the Campbell Plateau.

Tectonic development of the Austral–Antarctic Gondwana margin

The interpretation of crustal structure along the transects in the CTM, NVL and SEA form the basis of a model for the tectonic evolution of a major part of the Gondwana margin from Proterozoic to middle Paleozoic time. This model involves continental growth by accumulation and deformation of marginal sediments and by tectonic accretion of allochthonous terranes. In as much as it involves development of a continental margin, our model is similar to those of Elliott (1975) and Stump (1976, 1982). However, a more comprehensive description of the tectonic elements and identification of major allochthonous crustal blocks has been achieved by our isotopic studies. The Proterozoic to middle Paleozoic evolution of the Gondwana margin is outlined in Fig. 7. The CTM forms the foundation for our tectonic model for this time period because it contains the largest cross-structural exposure of the Delamerian–Ross Orogenic Belt and because it contains the best regional coverage of Nd, Sr, and O isotopic data on granites (see Borg et al., 1990).

The first part of the model deals with events that produce the basement elements that comprise the margin of the East Antarctic Craton. The earliest event is deposition of sediments and volcanics of the Miller Formation (Fig. 7A). The tectonic setting inferred for the earliest recorded orogenic phase is represented in Fig. 7B. Prior to 1.7 Ga, a compressive margin developed. In the upper crust, the sedimentary and volcanic rocks were folded prior to 1.7 Ga and at 1.7 Ga they were intruded by a granodiorite derived from Archean basement (star in Fig. 7B). Because of its crustal origin, we infer that the granodiorite was emplaced within the inboard part of the margin. Concurrently, igneous material from the mantle was added to, and mixed with, the Archean material in the lower crust at the margin. This process resulted in the production of a fringe of continental basement with a Sm–Nd model age of 2 Ga. A similar model is used to explain Proterozoic provinces at the fringes of Archean cratons in North America (cf. Bennett and DePaolo, 1987; Patchett and Arndt, 1986).

The next phase in the model treats the late Proterozoic and early Paleozoic magmatism and tectonic accretion events that lead to the present configuration of terranes. It begins with deposition of the Argosy, Cobham, and Cotton Plateau-type Goldie Formations along a new continental margin (Fig. 7C). These formations are the greenschist-facies metamorphic rocks now exposed along the boundary between the Miller Range Block and the Beardmore Glacier Block of Borg et al. (1990). The depositional setting represents an early phase of development of the province referred to as the Gondwana margin geocline in Fig. 2 and it may have been created by rifting along the margin prior to about 750 Ma. Rifting removed an outboard portion of the previously formed continental margin complex leaving the Archean to early Proterozoic metamorphic rocks of the Miller Range exposed at the margin as a sedimentary source for the Argosy Formation and leaving the recently formed 2 Ga lower crustal province at the edge of the continental basement. The isotopic compositions of the basalt and gabbro associated with the Cotton Plateau-type Goldie Formation at Cotton Plateau indicate an oceanic setting at ca. 750 Ma which is consistent with our interpretation of a continental margin depositional setting.

Between about 750 and 570 Ma a convergent margin developed again along this portion of the Gondwana margin (Fig. 7D). This tectonic regime, referred to as the Beardmore Orogeny, resulted in folding of the Argosy, Cobham, and Cotton Plateau-type Goldie Formations (Fig. 7C) and in accretion of an allochthonous continental block, the Beardmore Microcontinent, which is now represented by the Beardmore Glacier and Gabbro Hills Blocks and by the eastern-type Goldie Formation in the CTM (Fig. 7E). The deformed sediments were squeezed up between the cratonic margin and the Beardmore Microcontinent, producing eastward verging structures ascribed to the Beardmore Orogeny. Southeastward overthrusting of Archean amphibolite-grade gneisses over Proterozoic crystalline rocks on the Endurance thrust in the Miller Range may also have occurred during this orogenic phase (cf. Grindley, 1972; Goodge et al., 1989). The Carlyon Granodiorite, a deformed granitic complex in the Darwin Glacier area (star in Fig. 7D), has yielded a Rb–Sr whole rock isochron of 568 ± 10 Ma (Felder and Faure, 1980) and is the only known candidate for magmatism related to the Beardmore Orogeny.

By early Cambrian time deposition of carbonates and associated clastic sediments was occurring along the Gondwana margin (Fig. 7F). In the CTM these rocks include the Byrd Group (shelf limestone) inboard on the margin and, possibly, the Liv Group (volcanic, volcaniclastic and carbonate rocks) in an outboard setting (cf. Rowell and Rees, 1989). The Wilson Group, in NVL, and the Adelaide Supergroup, the Kanmantoo Group, and the Glenelg River Complex, in SEA (Stump et al., 1986), represent the northern continuation of this tectonodepositional province. By late Cambrian time, calc-alkaline volcanism (represented by rocks in the Liv Group) had begun in the outboard part of the CTM indicating the onset of subduction in a new convergent tectonic regime along the margin. Folding of these late Precambrian and Cambrian rocks occurred along the Austral–Antarctic margin as the Delamerian and Ross Orogenies (Fig. 7G). Orogenic activity culminated with emplacement all along the margin of granitic plutons at ca. 500 Ma.

The next phase of continental margin development is the emplacement of the allochthonous continental collage represented by the Grampians–Stavely and Stawell Terranes and the Lachlan province in SEA, and by the Bowers, Robertson Bay and Surgeon Island Terranes in NVL (Fig. 2 and 6). The northwestern portion of Marie Byrd Land may also be part of this collage. The early to middle Paleozoic development of these terranes, prior to final emplacement against Gondwana, is outlined in Fig. 8. Our model for the development of this region prior to emplacement of the Admiralty Intrusive Complex (Fig. 8A–C) is similar to that summarized for SEA by Scheibner (1985, 1987), with development and closing of several oceanic basins, except that our model does not tie these events to the Gondwana margin and delays final emplacement of this continent until after the Devonian. The earliest phase of development of the allochthonous terrane collage is shown in Fig. 8A. Volcanics of the Bowers Terrane (NVL), and by correlation those of the Grampians–Stavely Terrane (SEA), developed initially as an oceanic arc (Weaver et al., 1984) and evolved to an Andean-type continental margin arc on the southwestern margin of a continental craton in early to middle Cambrian time (see Wodzicki and Robert, 1986, fig. 8). This probably occurred in association with northeastward subduction. In the late Cambrian a back-arc basin is inferred to have developed to the east of the volcanic arc in which turbidites of the Stawell Terrane (SEA) and the Robertson Bay Terrane (NVL) accumulated during Cambro-Ordovician time. In the Melbourne

Terrane, east of the Stawell Terrane (see Fig. 6), Nelson et al. (1984) inferred an oceanic back-arc setting for boninitic and tholeiitic lavas that underlie Cambro-Ordovician sediments. To the east of this volcanic arc and turbidite complex, Cambro-Ordovician sediments of the Lachlan province accumulated on or at the margin of a Proterozoic craton (see fig. 4 and 5 in Scheibner, 1985). In the NVL, this Proterozoic craton is represented by the Surgeon Island Terrane (see Fig. 6). Following deposition of the Cambro-Ordovician turbidites the terranes were assembled

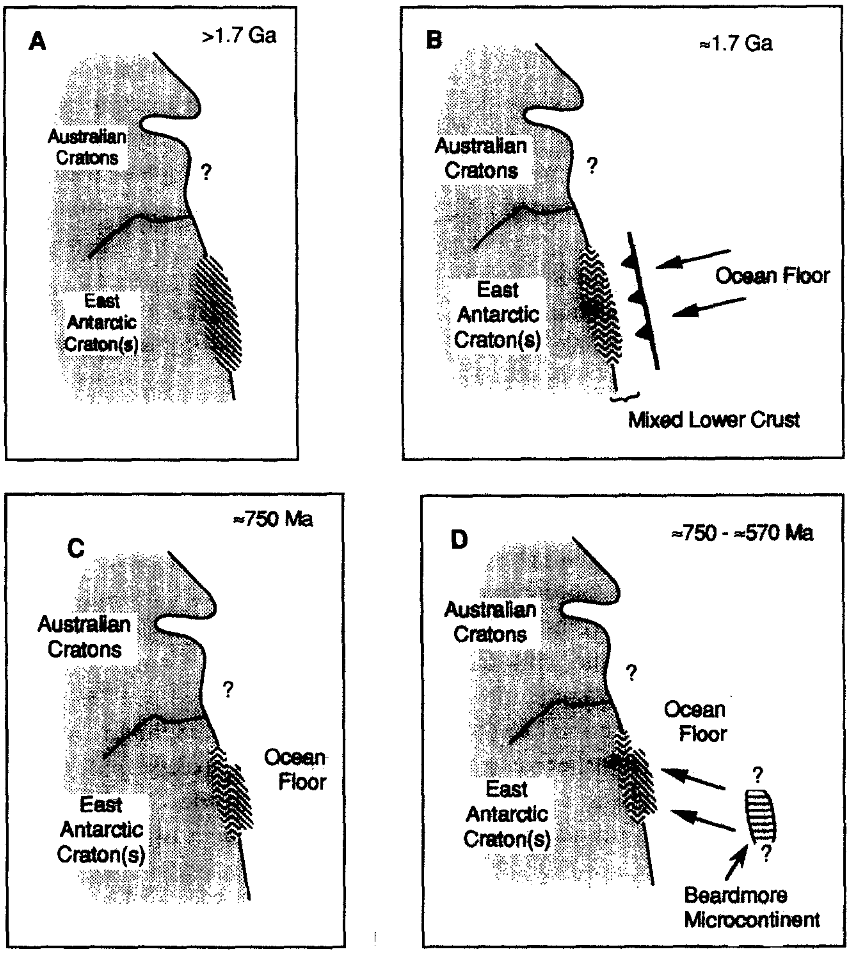


Fig. 7. Tectonic model for the development of the Austral-Antarctic segment of the Gondwana margin from Late Precambrian to early Paleozoic time. (A) Deposition of the Miller Formation. (B) At about 1.7 Ga, a compressive margin develops. Rocks at the margin are folded and intruded by granite (four-pointed star = granodioritic orthogneiss of the Miller Range). The lower crust becomes a mixture of new mantle-derived material and Archean material. The mixed lower crust has a Nd depleted-mantle model age of ca. 2 Ga. (C) Deposition of Argosy Formation, Cobham Formation and Cotton Plateau-type Goldie Formation at about 750 Ma. (D) A compressive margin develops again at about 600–560 Ma. Granitic magma is emplaced into the Darwin Glacier area (four pointed star). The Beardmore Microcontinent, represented by the Beardmore Glacier and Gabbro Hills Blocks and by the eastern-type Goldie Formation of the CTM develops somewhere off the margin of Gondwana. (E) The Beardmore Microcontinent is juxtaposed during this phase and the Argosy, Cobham, and Cotton Plateau-type Goldie Formations are squeezed-up between the allochthonous continental fragment and the Gondwana continent. An east vergent thrust fault (*f*), compatible with early east vergent folding of the rocks, is inferred as the boundary with the Beardmore Microcontinent. East-southeast-directed overthrusting develops in the Miller Range (Endurance thrust). (F) Deposition of early-middle Cambrian sediments takes place along the Austral-Antarctic margin of Gondwana. By late Cambrian time calc-alkaline volcanism has begun in the CTM, indicating onset of a convergent tectonic regime once again. (G) Folding of rocks along the Austral-Antarctic segment of Gondwana forms the Ross-Delamerian Orogens. These rocks are intruded by granitic plutons in Cambro-Ordovician time.

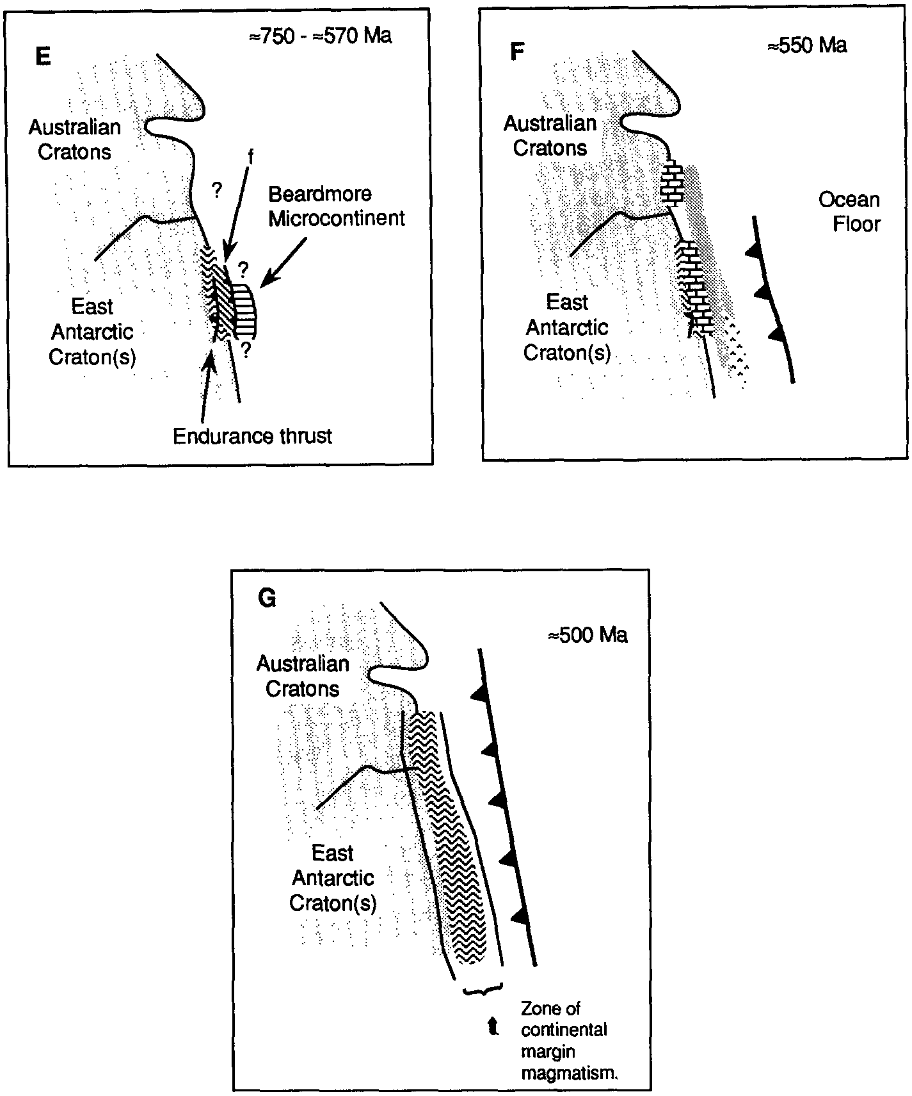


Fig. 7 (continued).

into the configuration shown in Fig. 8B. The Bowers Terrane was thrust eastward over the Robertson Bay Terrane in NVL (e.g. Gibson and Wright, 1985) and, by inference, the Grampians–Stavely Terrane was thrust eastward over the Stawell Terrane in SEA. This probably happened in early to middle Ordovician time as indicated by estimates of the age of folding in the Bowers and Robertson Bay Terranes (Adams et al., 1982; Adams and Kreuzer, 1984).

In SEA, the Heathcote greenstone belt represents the Cambrian ocean basin that existed between the Lachlan province and the Stawell Terrane. If our terrane correlations are correct, the extension of this greenstone belt should lie between the Robertson Bay and Surgeon Island Terranes in NVL. A candidate is the pillow lavas at Unger Island just west of Surgeon Island (Tessensohn, 1984, fig. 5), the type locality of the Surgeon Island Terrane. Although Tessensohn (1984) suggests that these lavas are an outlier of the Bowers Terrane, another interpretation is that they represent the southern continuation of the Heathcote greenstone belt and therefore mark a suture between the Robertson Bay and Surgeon Island Terranes. Sometime during middle Ordovician to early Silurian time a continental block is inferred to have existed to the southwest of this

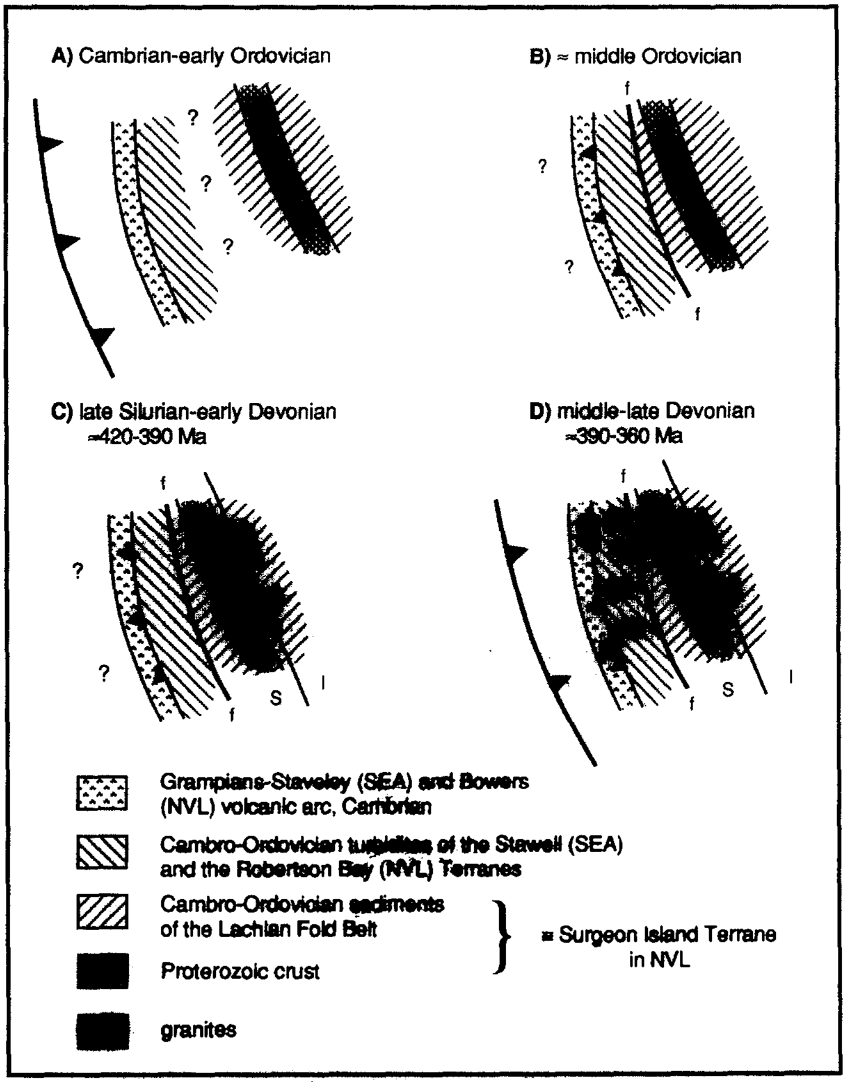


Fig. 8. Tectonic development of terranes of SEA and NVL allochthonous to pre-Devonian Gondwana. The inferred fault boundary between the Robertson Bay and Surgeon Island Terranes is labelled *f* in the sketch. See text for explanation. In (C) and (D) the boundary between the *I*- and *S*-type granites of SEA is shown.

terrane collage to provide a source of coarse clastic sediments for the upper units of the Bowers and Grampians–Stavely Terranes (Laird et al., 1982; Wodzieki and Robert, 1986; Stump et al., 1986).

Emplacement of the *I*- and *S*-type granites into the eastern Lachlan Fold Belt (SEA) occurred during Siluro-Devonian time (Fig. 8C). In the early to middle Devonian, the Admiralty Intrusive Complex was emplaced in NVL and similar plutons were emplaced in western and central Victoria, Australia. The range of Nd and Sr isotopic compositions and the polarity of the Admiralty Intrusive Complex indicates emplacement as a continental margin magmatic province with northeastward subduction beneath the terrane collage, or microcontinent (Fig. 8D).

Final assembly of the allochthonous terrane collage with Gondwana occurred by latest Devonian or Permian time (Fig. 9). The allochthonous terrane collage is now present in parts of Antarctica (part of NVL and probably Marie Byrd Land) and southeastern Australia (central and eastern Victoria, New South Wales, and

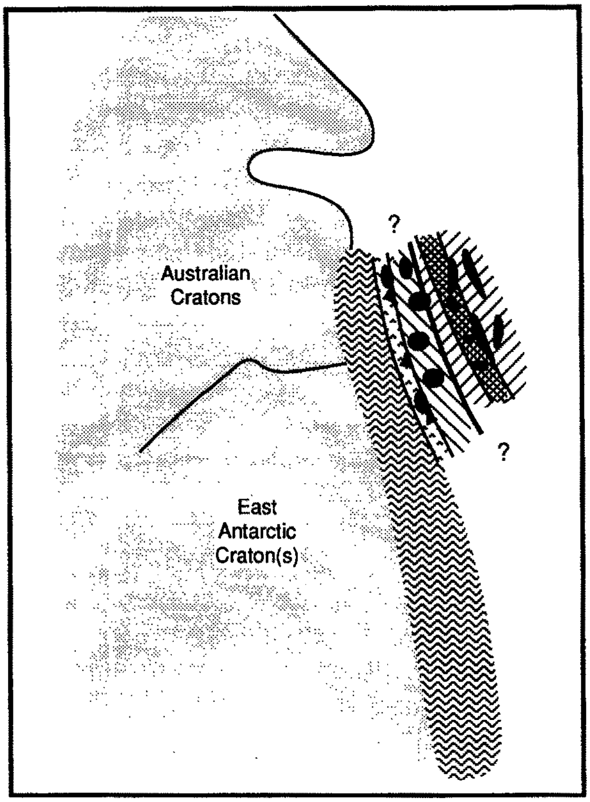


Fig. 9. Final assembly of the Austral–Antarctic segment of the Gondwana margin. Ornament as in Fig. 7 and 8. See text for explanation.

Tasmania), and may be present in New Zealand, the Campbell Plateau, and the Lord Howe Rise.

Implications for future work

The tectonic model presented here raises a number of issues. For example, the identification of the Beardmore Microcontinent and its allochthonous nature requires a reevaluation of traditional views of the geologic development in the CTM (see Borg et al., 1990). However, the timing of accretion of the Beardmore Microcontinent is poorly constrained and the relationship between accretion, deformation, and magmatism along the Gondwana margin in latest Precambrian time is obscure. The Goldie Formation, as traditionally interpreted, must represent at least two unrelated tectonodepositional environments whose structural relationship is not known. One environment, represented by the Argosy, Cobham, and Cotton Plateau-type Goldie Formations, developed in association with the Gondwana margin in our model. A parautochthonous origin for these formations is implied but a more complex history might be involved. The second environment, represented by the eastern-type Goldie Formation, developed in association with the Beardmore Microcontinent in our model. Thus, the model implies the existence of a previously unrecognized, but potentially mappable, suture situated between the Cotton Plateau and the mouth of the Nimrod Glacier. This stratigraphy and origin of other sedimentary rocks correlative with the traditional Goldie Formation should also be reevaluated.

Other issues arise from aspects of the tectonic model that are based on interpretations in NVL. For example, based on our model, the granites of the Delamerian Terrane, Grampians–Stavely Terrane, Stawell Terrane, and western Lachlan province in SEA should show regional patterns of isotopic and chemical compositions similar to the granites in NVL. Of particular importance to testing and revising the proposed model are (1) the petrogenesis of mafic and ultramafic rocks along the eastern margin of the Wilson Terrane which are inferred to be remnants of oceanic crust, (2) the petrogenesis of the mafic igneous rocks of the Bowers and Grampians–Stavely Terranes which are inferred to represent an island arc, (3) the provenance of the metasedimentary rocks of the Bowers and Grampians–Stavely Terranes, (4) the origin of the pillow lavas at Unger Island which are inferred to be correlative with the Heathcote greenstone belt and to represent an old suture, and (5) the provenance of metasedimentary rocks of the Surgeon Island Terrane and their relationship with turbidites of the Robertson Bay Terrane and metasediments of the Lachlan province.

Conclusion

Isotopic studies of granitic rocks in Antarctica provide a basis for defining age provinces in the pre-batholithic lower crust. In conjunction with other geological constraints the new data allow us to construct an improved model for the late Precambrian and early Paleozoic tectonic development of the Antarctic segment of the Gondwana margin. Major features of the new model are: (1)

the accretion of at least one allochthonous crustal block in the central Transantarctic Mountains during development of the late Precambrian and early Paleozoic continental margin, and (2) a complex allochthonous terrane collage containing Proterozoic basement which was emplaced in its final position in northern Victoria Land after the Devonian. Terrane correlations allow the model to be extended northward into Australia and southeastward into Marie Byrd Land from northern Victoria Land. Thus, the model implies that the regions east of the Delamerian Terrane in southeastern Australia are allochthonous to pre-Devonian Australia and that Marie Bryd Land is also part of the allochthonous terrane collage. The model is currently speculative, but it provides a framework for more focussed and problem-oriented research. Several elements of the model could be tested by further isotopic studies of granitic rocks, provenance studies of the metasedimentary rocks (especially in key boundary areas), and studies aimed at determining the origin and tectonic setting of the meta-igneous rocks of the various terranes.

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