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View of the Transantarctic Mountains to the northwest from the summit of Mt. Griffith (3095 m, lat 85°53′S, long 155°30′W). Most of the exposure in the foreground is plutonic rock of the Ross orogen. The dark cliffs of Breyer Mesa in the background are topped by an exhumed part of the mid-Paleozoic Kukri peneplain, formed by erosion following the Ross orogeny. On the skyline is the Rawson Plateau, containing late Paleozoic to Triassic sedimentary rocks of the Beacon Supergroup which overlie the unconformity. Amundsen Glacier flows from left to right in the middle ground of the photo. *Photo by Ed Stump.*

The Ross Orogen of the Transantarctic Mountains in Light of the Laurentia-Gondwana Split

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ABSTRACT

The recent hypothesis that the margins of the western United States and Antarctica were conjugate prior to the breakout of Laurentia from Gondwana is consistent with the record of events in the Late Proterozoic–early Paleozoic Ross orogen of the Transantarctic Mountains. Isotopic data indicate that basement to the Ross orogen is 2.0–1.7 Ga continental crust, temporarily matching basement in the southwestern United States. The onset of activity in the Ross orogen was Late Proterozoic basin development with widespread deposition of turbidites. Rifting within this basin is indicated by bimodal volcanism dated at ~750 Ma, coincident with volcanism in the basal Windermere Supergroup in North America. Actual separation is presumed to have occurred shortly before accumulation of Early Cambrian platform carbonates on the margins of both continents. Subsequent to this, the histories of the two margins evolved independently. Limited data indicate that plutonism had begun in the Ross orogen by ~550 Ma. By the Middle Cambrian an association of carbonates and bimodal volcanics was accumulating outboard of the Early Cambrian carbonate platform. Deformation, metamorphism, and voluminous plutonism culminated during the Late Cambrian with cooling ages ~500 Ma. This activity, recorded throughout widespread parts of Gondwana, occurred while the western margin of Laurentia remained passive.

INTRODUCTION

Marking the boundary between East and West Antarctica, the Transantarctic Mountains are a major intracratonic chain that extends for 3500 km across Antarctica, reaching heights >4000 m (Fig. 1). The interior or plateau flank of the Transantarctic Mountains dams the East Antarctic Ice Sheet; the front of the range rises with spectacular escarpments from the Ross and Weddell embayments and the intervening West Antarctic Ice Sheet. The present-day mountains have undergone episodic uplift since the Early Cretaceous (Stump and Fitzgerald, 1992) and have been modeled as a major rift shoulder structure (Fitzgerald et al., 1986; Stern and ten Brink, 1989). The unifying geological feature of the mountains is a middle Paleozoic erosion surface (Kukri peneplain) that separates gently tilted, Devonian to Triassic sedimentary rocks (Beacon Supergroup) and Jurassic continental tholeiites (Ferrar Group) from a Proterozoic to early Paleozoic orogenic belt (Ross orogen) (see photograph). The recent hypothesis (SWEAT) by Moores (1991), amplified by Dalziel (1991) and Hoffman (1991), that the western United States was contiguous with Antarctica during the Proterozoic, with subsequent rifting and continental drift, provides a powerful framework for interpretation of the geological history of the Ross orogen of the Transantarctic Mountains.

On a local scale, mapping in these mountains is similar to the Basin and Range, in that very good outcrops are separated by expanses of cover (ice or alluvium). On a continental scale, however, the breadth of the Transantarctic Mountains is narrow (300–0 km) compared to the Cordillera, so the spatial

Ross Orogen *continued on p. 26*

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IN THIS ISSUE

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Ross Orogen *continued from p. 25*

record of the Ross orogen is incomplete, and the continuity of certain tectonostratigraphic sequences along the mountains is not observable. Nevertheless, the present-day Transantarctic Mountains appear to follow closely the axis of the Ross orogen, with younger accreted and/or displaced blocks composing West Antarctica, and Proterozoic and Archean cratonic rocks making up the outcrops around the perimeter of East Antarctica, and presumably the crust beneath the East Antarctic Ice Sheet.

A long-standing view of the Ross orogen is that it developed along a passive continental margin that was affected by two orogenic episodes (e.g., Elliot, 1975)—the first in the Late Proterozoic (Beardmore orogeny), and the latter in Cambrian-Ordovician time (Ross orogeny). How the passive margin originated was not directly considered. Moreover, interpretations of the timing and extent of the Beardmore orogeny have undergone repeated revisions, and the true nature of this event is still uncertain.

GEOLOGIC HISTORY

Sm-Nd model ages from granitic rocks in northern Victoria Land and the central Transantarctic Mountains suggest that continental crust of Early Proterozoic age (2.0–1.7 Ga) underlies most of the mountain range (Borg et al., 1990; Borg and DePaolo, 1991). The same technique indicates that much of the Cordillera in the southwestern United States is underlain by rocks of similar age (Bennett and DePaolo, 1987). A Proterozoic supercontinent with these two areas matched is supported by these data. Direct links of age provinces may be difficult, however, for as Borg and DePaolo (1991) point out, fragments may have been displaced obliquely along the margins during the breakup.

The one place in the Transantarctic Mountains where Early Proterozoic age rocks are known in outcrop is in the Miller and Geologists ranges, where a varied suite of multiply deformed, high-grade metamorphic rocks (Nimrod Group) is dominated by quartzofeldspathic schists and gneisses, but includes amphibolites, marbles, calcschists, and quartzites. The rocks carry a pervasive shear fabric through much of their outcrop (Goodge et al., 1991). A Pb-Pb zircon age on the Aurora orthogneiss indicates magma generation within part of the Nimrod Group at ~1.7 Ga (Goodge et al., 1991). It is possible that metamorphic rocks with similar lithologies (Koettlitz and Skelton groups) cropping out throughout southern Victoria Land are correlative with the Nimrod Group. In various studies the Koettlitz and Skelton groups have been considered to be higher grade equivalents of Late Proterozoic pelites and Cambrian carbonates exposed to the south of Byrd Glacier (e.g., Grindley, 1981; Laird, 1981), although no fossils have been found in the carbonates to substantiate this. Recently, Rowell et al. (1991) demonstrated that the Skelton Group underwent multiple deformation during the Proterozoic. This precludes a Cambrian age and suggests correlation with Nimrod Group, but early Beardmore sedimentation (see below) is another possibility for the metasedimentary rocks in southern Victoria Land.

The initial sedimentation in the Ross orogen occurred in a deep-water basin parallel to the Transantarctic Mountains, in which quartzose turbidites of the Beardmore Group were deposited from the Pensacola Mountains (Patuxent Formation) through the Queen Maud Mountains (La Gorce Formation) to at least the central Transantarctic Mountains (Goldie Formation) (Schmidt et al., 1965; Smit and Stump, 1986: Gunn and Walcott, 1962). These rocks are lacking in rock fragments and have a lithology characteristic of a metamorphic-plutonic source. Conformably underlying the Goldie Formation in the Cobham Range, just outboard of the Miller and Geologists ranges, is the Cobham Formation, containing carbonates, quartzites, and pelites indicative of a shallow-water, marginal facies of the basin (Laird et al., 1971). Whether these rocks have exposed correlatives in southern Victoria Land, as mentioned above, or in northern Victoria Land, as discussed below, is uncertain. Of note, a diamictite of possible glaciogenic origin has been found within the Goldie Formation on Cotton Plateau in close proximity to marine volcanics (Stump et al., 1988).

That rifting occurred during formation of the Beardmore basin is suggested by bimodal volcanism in the Patuxent Formation (Storey et al., 1991), basalts in the Goldie Formation in the Ramsey Glacier area (Wade and Cathey, 1986), and bimodal volcanism in the Goldie Formation at Cotton Plateau (Stump et al., 1991). The basalts in the Goldie Formation are intruded by gabbro, both of which have Sm/Nd ratios and initial ε_{Nd} values indicative of generation in an oceanic setting (Borg et al., 1990). The basalts of the Patuxent Formation have continental affinities (Frischbutter and Vogler, 1985; Storey et al. 1991).

The best isotopic estimate of the age of the Beardmore Group is from a Sm-Nd mineral isochron on the gabbro within the Goldie Formation with a date of 762 ±24 Ma (Borg et al., 1990), indicating that sedimentation had begun by that time and suggesting that most if not all of the deposition occurred in the Late Proterozoic. On the basis of isotopic data from metasedimentary rock, Borg et al. (1990) suggested, pre-SWEAT, that the Beardmore basin was two sided, with a 1.7 Ga continental source for part of the Goldie Formation on the *outboard* (Ross Sea) side.

In western North America, two major sequences of noncrystalline, Proterozoic rocks occur within the Cordillera. Both are postulated to have been deposited in association with rifting events. The earlier suite, exemplified by the Belt and Purcell supergroups, is Middle Proterozoic and has no apparent counterparts in Antarctica.

The younger suite is represented by sequences at several widely separated localities in the United States, from Death Valley to Idaho, and by the relatively continuous belt of Windermere Supergroup in Canada and northeastern Washington. The sequences in the western United States appear to have been deposited in local basins or a shelf environment (Stewart, 1972), and in general apparently are lacking in turbidites, which are characteristic of all but the westernmost deposits in Antarctica. This may, however, simply reflect what parts of the rift basin are preserved on the respective continents. Presumably the basin deepened outboard of the deposits now seen in the western United States. An association of volcanics and diamictites, characteristic of the lower parts of the sequences in the western United States (Crittenden et al., 1971; Miller, 1985) finds its counterpart in the Goldie Formation of the Transantarctic Mountains.

Based on Sm-Nd and Rb-Sr dating of volcanics near the base of the Windermere Supergroup in northeastern Washington (Devlin et al., 1988), a recent estimate on the initiation of rifting on the North American side is about 750 ±30 Ma, coincident with the date on gabbro from Cotton Plateau. Magmatic rocks of this same age are found at several other localities farther to the north in the Canadian Cordillera (Roots and Parrish, 1988; Jefferson and Parrish, 1989).

The notion of a Late Proterozoic Beardmore orogeny in the Transantarctic Mountains was proposed by Grind-

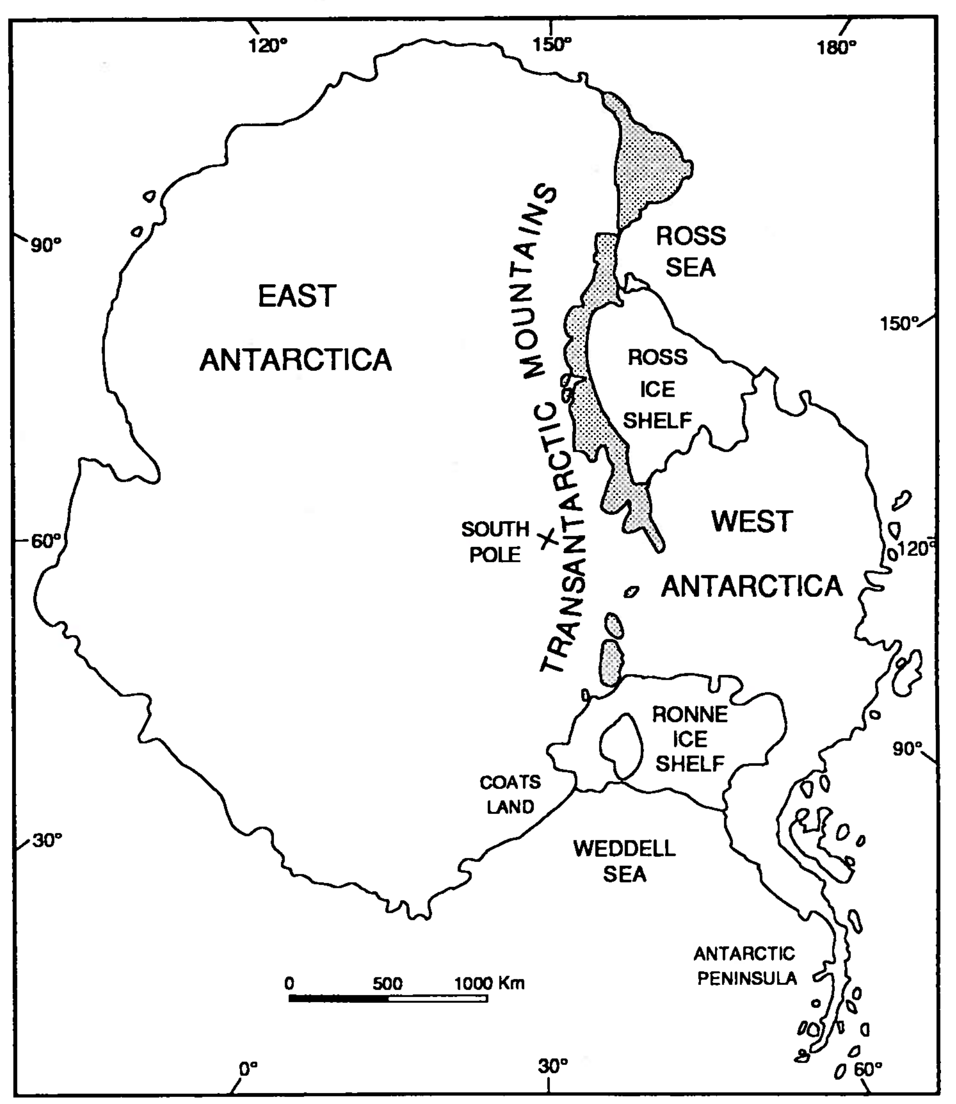

Figure 1. Location map for Antarctica. Shading indicates Transantarctic Mountains. Orientation of the continent with 150°E at the top was chosen for compatibility with maps in Figure 2.

ley and McDougall (1969). Evidence for deformation was angular unconformities with Lower Cambrian Shackleton Limestone overlying folded Goldie Formation in the Nimrod Glacier area (Laird et al., 1971) and Middle Cambrian Nelson Limestone over Patuxent Formation in the Pensacola Mountains (Schmidt et al., 1965). The age for this event was suggested as 680 to 620 Ma (Grindley and McDougall, 1969), on the basis of several isotopic determinations from silicic porphyries (Wyatt Formation and Thiel Mountains porphyry) in the Queen Maud and Thiel mountains (Ford, 1964; Faure et al., 1968) that had no known field relations to either the Beardmore Group or the Cambrian limestones. Subsequently, the Wyatt Formation was observed to intrude folded Beardmore Group rock (Stump et al., 1986), sedimentary rocks interbedded with the Thiel Mountains porphyry were found to contain fossils (Storey and Macdonald, 1987), and the age of the Thiel Mountains porphyry was revised to ~500 Ma (Pankhurst et al., 1988). Rowell et al. (1992) have pointed out that deformation of the Patuxent Formation is constrained only to have been pre–Nelson Limestone, and they have suggested that the folding in the Pensacola Mountains included a phase that was Early to Middle Cambrian.

Several angular contacts between Shackleton Limestone and underlying Goldie Formation were mapped in the Nimrod Glacier area as unconformities by Laird et al. (1971). In each of the localities where they have visited them, Rowell et al. (1986) have interpreted these contacts as tectonic. At a critical locality on the northwest flank of Cotton Plateau, the trough and eastern limb of a syncline of Shackleton Limestone overlies truncated Goldie Formation (Laird et al., 1971). The contact along the near-vertical limb was highly sheared, probably accompanying the folding. In the trough of the syncline, Shackleton Limestone is flat-lying and truncates recumbent folds in Goldie Formation. A yellow clay-rich zone marks the contact. The basal beds of Shackleton Limestone (micaceous sandstone) are not sheared, nor do they show other evidence of movement parallel to the contact with Goldie Formation. Stump et al. (1991) concurred with Laird et al. (1971) that the contact is an angular unconformity, but in light of accumulating evidence, reinterpretation as a thrust fault might be warranted. Accepting that all contacts of Shackleton Limestone and Goldie Formation are tectonic still does not preclude the possibility of folding of the Goldie Formation prior to deposition of Shackleton Limestone, but also the Goldie folding may have followed Shackleton deposition with subsequent juxtaposing of the two formations.

The Cotton Plateau locality is unique in that only there have two episodes of deformation been demonstrated in Goldie Formation rocks (Stump et al., 1991). Elsewhere only one generation of folding has been reported for the Goldie (Gunn and Walcott, 1962; Grindley, 1963; Laird, 1963), throughout and adjacent to a broad area of infolded Shackleton Limestone, whose deformation is, by definition, Ross orogeny. The earlier folding of Goldie Formation at Cotton Plateau may be the same generation as is seen elsewhere in the Goldie, and the younger deformation (primarily cleavage and mesofolds) may be a local feature related to the shearing in the eastern limb of the Shackleton syncline.

As can be seen, the concept of the Beardmore orogeny as a Late Proterozoic episode, distinct from the Cambrian-Ordovician Ross orogeny, has become blurred. As one focuses on the separation of Gondwana and Laurentia, the uncertainty of the absolute age of the Cambrian-Precambrian boundary and the duration of the Cambrian period loom as other obstacles to understanding the sequence of events surrounding the breakup. Regardless of the details, however, it is apparent that once drift had begun, the North American margin remained passive while the Antarctic margin and a considerable part of the rest of the Gondwana supercontinent underwent intense orogenic activity.

On the basis of tectonic subsidence curves from all continents except Antarctica, Bond et al. (1984) estimated the global breakup of a supercontinent between 625 Ma and 555 Ma, with an estimate of 577.5 ±22.5 Ma for the western United States. The Harland et al. (1982) time scale was used to do projections, with an age of 590 Ma for the Precambrian-Cambrian boundary. On the basis of interpretations of stratigraphic sequences in the Adelaide fold belt, von der Borch (1980) postulated that breakup occurred in southeastern Australia at about the Precambrian-Cambrian boundary.

In the Early Cambrian, carbonates began to accumulate along the platform margins of both western North America and Antarctica, by which time presumably drift had begun. Except for similar, initial sedimentation, the newly formed continental margins evolved with distinct and independent histories. In the central Transantarctic Mountains, the Shackleton Limestone was deposited during a short interval between middle and late Early Cambrian (Atdabanian to Botomian), (Debrenne and Kruse, 1986; Rowell et al., 1988; Rowell and Rees, 1989; Rees et al., 1989). The only other known, in situ Early Cambrian limestones in the Transantarctic Mountains are found in the Argentina Range to the northeast of the Pensacola Mountains (Rowell et al., 1992). One may postulate continuity of an Early Cambrian carbonate shelf spanning these localities, since the 1200 km distance between them is covered by rocks of the Beacon Supergroup and by ice.

A continuation of Shackleton Limestone to outcrops north of Byrd Glacier, however, would appear not to be justified. Some marbles do exist in the Koettlitz and Skelton groups of southern Victoria Land (Findlay et al., 1984), but they are not nearly as extensive as the Shackleton Limestone and are interbedded with clastic metasedimentary rock, arguing for their correlation with parts of the Nimrod Group or lower Beardmore Group. Furthermore, deformed Skelton Group is intruded by granite with a crystallization age of 500 ±4 Ma (Rowell et al., 1991). Several authors (Grindley and Laird, 1969; Grindley, 1981; Borg et al., 1989) have suggested that the marked geologic discontinuity that occurs across Byrd Glacier, with metamorphosed Skelton Group extensively intruded by plutonic rocks to the north and folded, low-grade to unmetamorphosed Shackleton Limestone to the south, is the result of right-lateral, strike-slip displacement. However, this may also reflect angular irregularities in the original continental margin that occurred during the breakup. No platform carbonates resembling Shackleton Limestone occur in northern Victoria Land.

Outboard of the Early Cambrian platform deposits are carbonates of Middle Cambrian age, including parts of the Liv Group of the Queen Maud Mountains (Stump, 1982) and the Nelson Limestone of the Pensacola Mountains (Schmidt et al., 1965). Both the Nelson Limestone and the Leverett Formation of the Liv Group are dated, from trilobites, as Middle Cambrian (Palmer and Gatehouse, 1972). In addition to its carbonates, the Liv Group also contains appreciable coarse-grained

Ross Orogen *continued on p. 30*

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The Geological Society of America is accepting applications for the 1992–1993 Congressional Science Fellowship. The Fellow selected will spend a year (September 1992–August 1993) in the office of an individual member of Congress or a congressional committee. The program provides an opportunity to gain a better understanding of science and technology issues facing Congress and to advise on a wide range of scientific issues as they pertain to public policy questions. The American Association for the Advancement of Science conducts an orientation program and assists the Fellow seeking a congressional staff position in which he or she can work on major legislative issues.

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Applications should be made by ***February 28, 1992.*** The applicant should write a letter stating her background, career goals and objectives, how she will use the money, and an explanation of the length and nature of the interruption in her education. The applicant should also submit two letters of reference. The first, from her thesis advisor, should include when the candidate will finish her degree, what requirements are as yet unfinished, and a statement of the candidate's prospect for future contributions to the geosciences.

For information on obtaining an application or for additional information, please contact: Chrysalis Scholarship, Association for Women Geoscientists Foundation, Macalester College Geology Dept., 1600 Grand Ave., St. Paul, MN 55105-1899.

Ross Orogen *continued from p. 27*

arenites, but the predominant lithology is a bimodal suite of volcanics with voluminous rhyolites and lesser basalts (Stump, 1985). This volcanic activity may represent lingering extensional effects of the breakup located in outer parts of the Antarctic continental margin (Dalziel, 1991).

Northern Victoria Land is composed principally of three terranes, of which the eastern two (Bowers and Robertson Bay) are allochthonous and were emplaced after or during the late stages of the Ross orogeny (e.g., Bradshaw et al., 1985; Gibson and Wright, 1985; Kleinschmidt and Tessensohn, 1987). The western, autochthonous Wilson terrane is underlain by schists and gneisses (Wilson and Lanterman metamorphics, Priestley Schist) whose protoliths were mainly graywacke and shale, with some calcareous parts. For the most part, these rocks were multiply deformed and metamorphosed during one prograde metamorphic episode to amphibolite facies (Kleinschmidt and Skinner, 1981). The majority of the K-Ar and Rb-Sr mineral dates from the Wilson terrane are between 500 and 470 Ma, typical of cooling following the Ross orogeny (Kreuzer et al., 1987). Limited Rb-Sr, whole-rock isochron dates indicate that metamorphism may have begun in places as early as 550 Ma (Adams and Hörndorf, 1991). A preliminary report of organic fragments from the Priestley Formation indicates a post-Precambrian age (Lombardo et al., 1989). The metasedimentary rock of the Wilson terrane may be Proterozoic, Early Cambrian, or both, and may straddle or postdate the continental breakup. In South Australia, by comparison, Late Proterozoic Adelaidean shelf sedimentary strata are followed by turbidites of the Early Cambrian Kanmantoo Group (von der Borch, 1980). Apparently, the depositional setting in northern Victoria Land following the breakup was quite different from that recorded throughout the rest of the Transantarctic Mountains.

The passive or extensional continental margin changed to one of subduction with resultant compressive deformation, metamorphism, and magmatism of the Ross orogeny. The simplistic view of a Cambrian-Ordovician episode that began with folding of Early and Middle Cambrian sedimentary rocks and ended with cooling of metamorphic and plutonic rocks around 510–470 Ma has been expanded by ongoing research to recognize multiple tectonic events, manifested either locally or throughout the Transantarctic Mountains.

The onset of activity is difficult to place. Age determinations on several plutonic rocks from northern and southern Victoria Land are older than most throughout the Ross orogen. These include the Sturgeon Island granodiorite (599 ±21 Ma; Rb-Sr, whole-rock isochron; Vetter et al., 1984), deformed, plutonic rocks of the Wilson terrane (544 ±4 Ma, U-Pb, zircon; Black and Sheraton, 1990), the Carylon granodiorite (568 ±10 Ma; Rb-Sr, whole-rock isochron; Felder and Faure, 1980), and a granite intruding the Skelton Group (550 ±4 Ma; U-Pb, zircon; Rowell et al., 1991). Whether one uses the Harland et al. (1990) time scale, with the Precambrian boundary at 570 Ma, or that of Odin et al. (1983), with the boundary at 530 Ma, it would appear that plutonic activity had begun in parts of the orogen before deposition of Early Cambrian Shackleton Limestone.

Deformation took various forms throughout the Transantarctic Mountains. A major shear zone in the Proterozoic Nimrod Group of the Miller and Geologists ranges has long been recognized; thrusting is thought to have occurred during the Early to Middle Proterozoic formation of the metamorphic rocks (Grindley, 1972). Goodge et al. (1991) demonstrated a considerably oblique component to the movement with a left-lateral sense relative to the axis of the Transantarctic Mountains. Stump et al. (1991) suggested that this shearing was coincident with the older deformation (Beardmore orogeny) of the Goldie Formation at Cotton Plateau. Most recently, Walker and Goodge (1991) have presented U-Pb age data, on zircons from plutons bearing the shear fabric, that indicate magmatic crystallization at 540 to 534 Ma. These new data push the shear zone development in the Miller Range into the framework of the early Ross orogeny, and out of the range of the traditional Beardmore orogeny or older events. Again, how this movement is interpreted with respect to the deposition of the Early and Middle Cambrian limestones of the Transantarctic Mountains depends on the time scale used. On the basis of isotopic data, Borg et al. (1990) have postulated a major lower crustal boundary and suture zone along Marsh Glacier, between the Miller Range and Cotton Plateau. It is possible that this juxtapositioning was early-Ross rather than Beardmore or earlier, as previously thought.

In the Nimrod Glacier area Shackleton Limestone is tightly folded. Overlying an erosion surface on Shackleton Limestone is the Douglas Conglomerate, which contains clasts of folded Shackleton Limestone, but no fossils to help determine its age (Rees et al., 1987). The Douglas itself has been deformed at least twice prior to deposition of the Beacon Supergroup. The composition of the Douglas (Pankhurst and Rees, 1991), the multiple, nonmetamorphic deformations of the Shackleton and Douglas, the apparent simplicity of deformation in the lower lying Goldie Formation, the tectonic character of most, if not all, of the observed contacts between the Goldie and the Shackleton, and the geometry and style of folding suggest a foreland fold and thrust belt.

Thrust faulting has been identified at two places in the central Transantarctic Mountains. In the Duncan Mountains, Duncan Formation is thrust over Fairweather Formation (Liv Group) (Stump, 1981). Traditionally, Duncan Formation has been correlated with Beardmore Group (Stump, 1982), but it could represent a Cambrian slope sequence deposited outboard of the belt of volcanics and carbonates of Liv Group, and later thrust upon it. At the head of Scott Glacier, La Gorce Formation (Beardmore Group) is thrust over Wyatt Formation (Stump et al., 1986). Wyatt Formation is undoubtably correlative with the Thiel Mountains porphyry, which recently has been dated at 493 ±24 Ma (Pankhurst et al., 1988); thus, this fault occurred late in the sequence of events that are encompassed by the Ross orogeny. In the central Scott Glacier area, a right-lateral, strike-slip fault has juxtaposed La Gorce and Wyatt formation rocks (Stump and Fitzgerald, 1988).

In the Pensacola Mountains, Middle Cambrian Nelson Limestone and overlying silicic volcanics (Gambacorta Formation) were folded into open structures during the traditional Ross event (Schmidt et al., 1978). Constrained as only pre–Middle Cambrian by the unconformity beneath Nelson Limestone, the folding of Patuxent Formation could be an Early Cambrian rather than a Late Proterozoic event, as suggested by Rowell et al. (1992).

Regardless of the structural variations along the Transantarctic Mountains, a tremendous pulse of magmatism ended the Ross orogeny (e.g., Borg et al., 1987); K-Ar and Rb-Sr dates are largely between 510 and 470 Ma (Stuiver and Braziunas, 1985). As research in these mountains continues, it may be useful to subdivide the Ross orogeny, as has been done for orogenic episodes in the Cordilleran, for it has become increasingly apparent that its evolution was complex and varied in both space and time. The history of the Ross orogen spans the breakout of Laurentia from Gondwana, the period of greatest complexity having occurred after the split as the newly formed margin rearranged itself. If the magmatic activity at about 750 Ma in both the Transantarctic Mountains and western North America signals the onset of rifting, then the rift to drift transition took perhaps as much as 200 m.y.

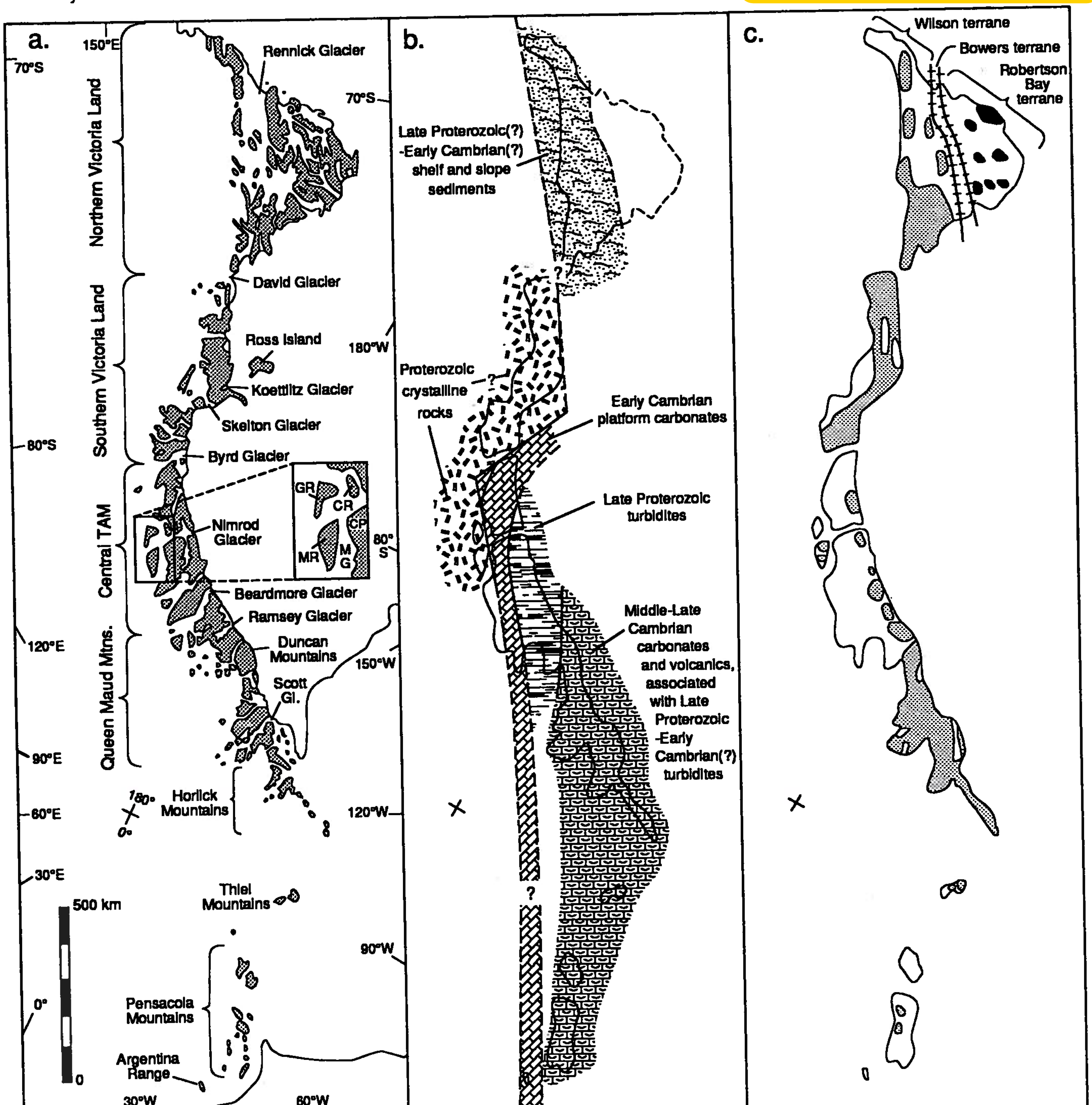

Figure 2. a: Location map for Transantarctic Mountains. CP = Cotton Plateau, CR = Cobham Range, GR = Geologists Range, MG = Marsh Glacier, MR = Miller Range. **b:** Principal lithotectonic divisions of the Ross orogen in the Transantarctic Mountains. **c:** Shading indicates outcrop areas of plutonic rocks of the Ross orogen with ±500 Ma cooling ages. Terrane boundaries are indicated for northern Victoria Land. Black indicates Devonian plutonic rocks in northern Victoria Land.

PANNOTIOS TECTONISM

The Ross orogeny of the Transantarctic Mountains is the Delamerian orogeny of Australia (Rutland et al., 1981). It is the Pan-African of Africa

(Kennedy, 1964) and the Brasiliano of South America (Cordani et al., 1973). It is an episode of continental crustal consolidation as great as any in Earth history. Besides the development of interconnected zones of high mobility, large parts of the cratonic nuclei were thermally reactivated. Throughout a large sector of coastal East Antarctica (long 0° to 110°E), the K-Ar dates on Archean and Early Proterozoic cratonic rocks are ±500 Ma (Craddock, 1972). Mobile belts in South America and Africa had begun orogenic activity in the Proterozoic, at least as far back as 650 Ma (Cordani et al., 1973; Kröner et al., 1978). Compressive tectonics had begun in parts of Gondwana prior to the breakout of Laurentia and continued afterwards.

The culmination of activity prior to cooling ~500 Ma occurred as all the cratonic nuclei of Gondwana sutured together, producing the supercontinent, perhaps in a scenario similar to that proposed by Hoffman (1991), but including subduction and orogenic activity along the Pacific margin of Australia, Antarctica, and at least southern South America. Lacking an alternative, I proposed "Pannotios" (Greek: pan = all, notios = southern) as a unifying term to designate the cycle of tectonic activity common to the Gondwana continents that resulted in the formation of the supercontinent (Stump, 1987). Southern Hemisphere geologists have long recognized the common heritage shared by the southern continents (du Toit, 1937), but the SWEAT hypothesis expands our view to the global interconnectedness of events during the Late Proterozoic–early Paleozoic.

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REFERENCES CITED

Adams, C.J., and Hörndorf, A., 1991, Age of the metamorphic basement of the Salamander and Lanterman Ranges, northern Victoria Land, Antarctica, *in* Thomson, M.R.A., Crame, J.A., and Thomson, J.W., eds., Geological evolution of Antarctica: Cambridge, England, Cambridge University Press, p. 149–153.

Bennett, V.C., and DePaolo, D.J., 1987, Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping: Geological Society of America Bulletin, v. 99, p. 674–685.

Black, L.P., and Sheraton, J.W., 1990, The influence of Precambrian source components on the U-Pb zircon age of a Palaeozoic granite from northern Victoria Land, Antarctica: Precambrian Research, v. 46, p. 275–293.

Bond, G.C., Nickeson, P.A., and Kominz, M.A., 1984, Breakup of a supercontinent between 625 Ma and 555 Ma: New evidence and implications for continental histories: Earth and Planetary Science Letters, v. 70, p. 325–345.

Borg, S.G., and DePaolo, D.J., 1991, North America, Australia, and Antarctica as a Late Precambrian supercontinent: A discussion: Geological Society of America Abstracts with Programs, v. 23, no. 5, p. A305.

Borg, S.G., and DePaolo, D.J., 1991, A tectonic model of the Antarctic Gondwana margin with implications for southeastern Australia: Isotopic and geochemical evidence: Tectonophysics, v. 196, p. 339–358.

Borg, S.G., DePaolo, D.J., Wendlandt, E.D., and Drake, T.G., 1989, Studies of granites and metamorphic rocks, Byrd Glacier area: Antarctic Journal of the United States, v. 24, p. 19–21.

Borg, S.G., Stump., E., Chappell, B.W., McCulloch, M.T., Wyborn, D., Armstrong, R.L., and Holloway, J.R., 1987, Granitoids of northern Victoria Land, Antarctica: Implications of chemical and isotopic variations to regional crustal structure and tectonics: American Journal of Science, v. 287, p. 127–169.

Borg, S.G., DePaolo, D.J., and Smith, B.M., 1990, Isotopic structure and tectonics of the central Transantarctic Mountains: Journal of Geophysical Research, v. 95, p. 6647–6667.

Bradshaw, J.D., Weaver, S.D., and Laird, M.G., 1985, Suspect terranes in north Victoria Land, Antarctica, *in* Howell, D.C., Jones, D.L., Cox, A., and Nur, A., Circum-Pacific Terrane Conference, Proceedings: Stanford, California, Stanford University Press, p. 36–39.

Cordani, U. G., Amaral, G., and Kawashita, K., 1973, The Precambrian evolution of South America: Geologische Rundschau, v. 62, p. 309–317.

Craddock, C., 1972, Geological map of Antarctica, 1:5,000,000: American Geographical Society.

Crittenden, M.D., Jr., Schaeffer, F.E., Trimble, D.E., and Woodward, L.A., 1971, Nomenclature and correlation of some upper Precambrian and basal Cambrian sequences in western Utah and southeastern Idaho: Geological Society of America Bulletin, v. 82, p. 581–602.

Dalziel, I.W.D., 1991, Pacific margins of Laurentia and East Antarctica–Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent: Geology, v. 19, p. 598–601.

Debrenne, F., and Kruse, P.D., 1986, Shackleton limestone archaeocyaths: Alcheringa, v. 10, p. 235–278.

Devlin, W.J., Breuckner, H.K., and Bond, G.C., 1988, New isotopic data and a preliminary age for volcanics near the base of the Windermere Supergroup, northeastern Washington, U. S. A.: Canadian Journal of Earth Sciences, v. 25, p. 1906–1911.

du Toit, A.L., 1937, Our wandering continents: Edinburgh, Oliver & Boyd, 336 p.

Elliot, D.H., 1975, Tectonics of Antarctica: A review: American Journal of Science, v. 275A, p. 45–106.

Faure, G., Murtaugh, J.G., and Montigny, R.J.E., 1968, The geology and geochronology of the basement complex of the central Transantarctic Mountains: Canadian Journal of Earth Sciences, v. 5, p. 555–560.

Felder, R.P., and Faure, G., 1980, Rubidium-strontium age determination of part of the basement complex of the Brown Hills, central Transantarctic Mountains: Antarctic Journal of the United States, v. 15, p. 16–17.

Findlay, R.H., Skinner, D.N.B., and Craw, D., 1984, Lithostratigraphy and structure of the Koettlitz Group, McMurdo Sound, Antarctica: New Zealand Journal of Geology and Geophysics, v. 27, p. 513–536.

Fitzgerald, P.G., Sandiford, M., Barrett, P.J., and Gleadow, A.J.W., 1986, Asymmetric extension in the Transantarctic Mountains and Ross Embayment: Earth and Planetary Science Letters, v. 81, p. 67–78.

Ford, A.B., 1964, Cordierite-bearing, hypersthene-quartz monzonite porphyry and its regional importance, *in* Adie, R.J., ed., Antarctic geology: Amsterdam, North-Holland, p. 429–441.

Frischbutter, A., and Vogler, P., 1985, Contributions to the geochemistry of magmatic rocks in the upper Precambrian lower Paleozoic profile of the Neptune Range, Transantarctic Mountains, Antarctica: Zeitschrift für Geologische Wissenschaften, v. 13, p. 345–357.

Gibson, G.M., and Wright, T.O., 1985, The importance of thrust faulting in the tectonic development of northern Victoria Land, Antarctica: Nature, v. 315, p. 480–483.

Goodge, J.W., Borg, S.G., Smith, B.K., and Bennett, V.C., 1991, Tectonic significance of Proterozoic ductile shortening and translation along the Antarctic margin of Gondwana: Earth and Planetary Science Letters, v. 102, p. 58–70.

Grindley, G.W., 1963, The geology of the Queen Alexandra Range, Beardmore Glacier, Ross Dependency, Antarctica; with notes on the correlation of Gondwana sequences: New Zealand Journal of Geology and Geophysics, v. 6, p. 307–347.

Grindley, G.W., 1972, Polyphase deformation of the Precambrian Nimrod Group, central Transantarctic Mountains, *in* Adie, R.J., ed., Antarctic geology and geophysics: Oslo, Universitetsforlaget, p. 313–318.

Grindley, G.W., 1981, Precambrian rocks of the Ross Sea region: Royal Society of New Zealand Journal, v. 11, p. 411–423.

Grindley, G.W., and Laird, M.G., 1969, Geology of the Shackleton Coast: American Geographical Society Map Folio Series, Folio 12, XIV.

Grindley, G.W., and McDougall, I., 1969, Age and correlation of the Nimrod Group and other Precambrian rock units in the central Transantarctic Mountains, Antarctica: New Zealand Journal of Geology and Geophysics, v. 12, p. 391–411.

Gunn, B.M., and Walcott, R.I., 1962, The geology of the Mt. Markham Region, Ross Dependency, Antarctica: New Zealand Journal of Geology and Geophysics, v. 5, p. 407–426.

Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G., and Walters, R., 1982, A geologic timescale: Cambridge, England, Cambridge University Press, 131 p.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G., 1990, A geologic timescale 1989: Cambridge, England, Cambridge University Press, 263 p.

Hoffman, P.F., 1991, Did the breakout of Laurentia turn Gondwanaland inside-out?: Science, v. 252, p. 1409–1412.

Jefferson, C.W., and Parrish, R.R., 1989, Late Proterozoic stratigraphy, U-Pb zircon ages, and rift tectonics, Mackenzie Mountains, northwestern Canada: Canadian Journal of Earth Sciences, v. 26, p. 1784–1801.

Kennedy, W.Q., 1964, The structural differentiation of Africa in the Pan African (±500 m.y.) tectonic episode: University of Leeds, Research Institute of African Geology, Department of Earth Sciences, Annual Report, v. 8, p. 48–49

Kleinschmidt, G., and Skinner., D.N.B., 1981, Deformation styles in the basement rocks of north Victoria Land, Antarctica: Geologisches Jahrbuch, v. B41, p. 155–199.

Kleinschmidt, G., and Tessensohn, F., 1987, Early Paleozoic westward directed subduction at the Antarctic Pacific margin: Evidence from metamorphic belts in northern Victoria Land, *in* McKenzie, G.D., ed., Gondwana Six: Structure, tectonics and geophysics: American Geophysical Union Monograph 40, p. 89–106.

Kreuzer, H., Delisle, G., Fromm, K., Höhndorf, A., Lenz, H., Müller, P., and Vetter, U., 1987, Radiometric and paleomagnetic results from northern Victoria Land, Antarctica, *in* McKenzie, G.D., ed., Gondwana Six: Structure, tectonics, and geophysics: American Geophysical Union Monograph 40, p. 31–47.

Kröner, A., Halpern, M., and Jacob, R.B., 1978, Rb-Sr geochronology in favor of polymetamorphism in Pan-African Damara belt of Namibia (south West Africa): Geologische Rundschau, v. 67, p. 688–705.

Laird, M. G., 1963, Geomorphology and stratigraphy of the Nimrod Glacier, Beaumont Bay region, southern Victoria Land, Antarctica: New Zealand Journal of Geology and Geophysics, v. 6, p. 465–484.

Laird, M.G., 1981, Lower Palaeozoic rocks of Antarctica, *in* Harland, C. H., ed., Lower Paleozoic of the Middle East, Eastern and Southern Africa, and Antarctica: London, Wiley & Sons, p. 257-314.

Laird, M.G., Mansergh, G.D., and Chappell, J.M.A., 1971, Geology of the central Nimrod Glacier area, Antarctica: New Zealand Journal of Geology and Geophysics, v. 14, p. 427–468.

Lombardo, B., Cappelli, B., Carmignani, L., Gosso, G., Memmi, I., Montrasio, A., Palmeri, R., Pannuti, F., Pertusati, P.C., Ricci, C.A., Salvini, F., and Talarico, F., 1989, The metamorphic rocks of the Wilson terrane between David and Mariner Glaciers, north Victoria Land, Antarctica: Società Geologica Italiana, Memorie, v. 33, p. 99–130.

Miller, J.M.G., 1985, Glacial and syntectonic sedimentation: The upper Proterozoic Kingston Peak Formation, southern Panamint Range, eastern California: Geological Society of America Bulletin, v. 96, p. 1537–1553.

Moores, E.M., 1991, The southwest U.S.–East Antarctic (SWEAT) connection: A hypothesis: Geology, v. 19, p. 425–428.

Odin, G.S., Gale, N.H., Auvray, B., Brelski, M., Dore, F., Lancelot, J.R., and Pasteels, P., 1983, Numerical dating of the Precambrian-Cambrian boundary: Nature, v. 301, p. 21–23.

Palmer, A.R., and Gatehouse, C.G., 1972, Early and Middle Cambrian trilobites from Antarctica: U.S. Geological Survey Professional Paper 456-D, 37 p.

Pankhurst, R.J., Storey, B.C., Millar, I.L., Macdonald, D.I.M., and Vennum, W.R., 1988, Cambrian-Ordovician magmatism in the Thiel Mountains, Transantarctic Mountains, and implications for the Beardmore orogeny: Geology, v. 16, p. 246–249.

Panttaja, S.K., and Rees, M.N., 1991, Provenance, age, and tectonic setting of lower Paleozoic siliciclastics in the central Transantarctic Mountains: Geological Society of America Abstracts with Programs, v. 23, no. 5, p. A364.

Rees, M.N., Girty, G.H., Panttaja, S.K., and Braddock, P., 1987, Multiple phases of early Paleozoic deformation in the central Transantarctic Mountains: Antarctic Journal of the United States, v. 22, p. 33–35.

Rees, M.N., Pratt, B.R., and Rowell, A.J., 1989, Early Cambrian reefs, reef complexes, and associated facies of the Shackleton Limestone, Transantarctic Mountains: Sedimentology, v. 36, p. 341–361.

Roots, C.F., and Parrish, R.R., 1988, Age of the Mount Harper volcanic complex, southern Ogilvie Mountains, Yukon: Geological Survey of Canada Paper 88-2, p. 29–35.

Rowell, A.J., and Rees, M.N., 1989, Early Paleozoic history of the upper Beardmore Glacier area: Implications for a major Antarctic structural boundary within the Transantarctic Mountains: Antarctic Science, v. 1, p. 249–260.

Rowell, A.J., Rees, M.N., and Braddock, P., 1986, Pre-Devonian rocks of the central Transantarctic Mountains: Antarctic Journal of the United States, v. 21, p. 48–50.

Rowell, A.J., Rees, M.N., Cooper, R.A., and Pratt, B.R., 1988, Early Paleozoic history of the central Transantarctic Mountains: Evidence from the Holyoke Range, Antarctica: New Zealand Journal of Geology and Geophysics, v. 31, p. 397–404.

Rowell, A.J., Rees, M.N., Dubendorfer, E.M., and Wallin, E.T., 1991, The Skelton Group, Victoria Land: Precambrian deformation of the Proterozoic platform of greater Antarctica: Geological Society of America Abstracts with Programs, v. 23, no. 5, p. A306.

Rowell, A.J., Rees, M.N., and Evans, K.R., 1992, Evidence of major Middle Cambrian deformation in the Ross orogen, Antarctica: Geology, v. 20, p. 31–34.

Rutland, R.W.R., Parker, G.M., Pitt, G.M., Preiss, W.V., and Murrell, B., 1981, The Precambrian of South Australia, *in* Hunter, D.R., ed., Precambrian of the Southern Hemisphere: New York, Elsevier, p. 309–360.

Schmidt, D.L., Williams, P.L., Nelson, W.H., and Ege, J.R., 1965, Upper Precambrian and Paleozoic stratigraphy and structure of the Neptune Range, Antarctica: U.S. Geological Survey Professional Paper 525-D, p. D112–D119.

Schmidt, D.L., Williams, P.L., and Nelson, W.H., 1978, Geologic map of the Schmidt Hills quadrangle and part of the Gambacorta Peak quadrangle, Pensacola Mountains, Antarctica: U.S. Antarctic Research Program Map A-8.

Smit, J.H., and Stump, E., 1986, Sedimentology of the La Gorce Formation, La Gorce Mountains, Antarctica: Journal of Sedimentary Petrology, v. 56, p. 663–668.

Stern, T.A., and ten Brink, U.S., 1989, Flexural uplift of the Transantarctic Mountains: Journal of Geophysical Research, v. 94, p. 5733–5762.

Stewart, J.H., 1972, Initial deposits in the Cordilleran geosyncline: Evidence of a late Precambrian (<850 m.y.) continental separation: Geological Society of America Bulletin, v. 83, p. 1345–1360.

Storey, B.C., and Macdonald, D.I.M., 1987, Sedimentary rocks of the Ellsworth-Thiel Mountains ridge and their regional equivalents: British Antarctic Survey Bulletin, v. 76, p. 21–49.

Storey, B.C., Macdonald, D.I.M., Millar, I.L., Pankhurst, R.J., Alabaster, T., and Dalziel, I.W.D., 1991, Upper Proterozoic rift-related basin and bimodal volcanic sequences in the Pensacola Mountains, Antarctica: Precursor to Cambrian supercontinent breakup?: International Symposium on Antarctic Earth Sciences, 6th, Japan National Institute of Polar Research, Abstracts, p. 549–550.

Stuiver, M., and Braziunas, T.F., 1985, Compilation of isotopic dates from Antarctica: Radiocarbon, v. 27, p. 117–304.

Stump, E., 1981, Structural relationships in the Duncan Mountains, central Transantarctic Mountains, Antarctica: New Zealand Journal of Geology and Geophysics, v. 24, p. 87–93.

Stump, E., 1982, The Ross Supergroup in the Queen Maud Mountains, *in* Craddock, C.C., ed., Antarctic geoscience: Madison, University of Wisconsin Press, p. 565–569.

Stump, E., 1985, Stratigraphy of the Ross Supergroup, central Transantarctic Mountains, *in* Turner, M.D., and Splettstoesser, J.F., eds., Geology of the central Transantarctic Mountains: American Geophysical Union, Antarctic Research Series, v. 36, p. 225–274.

Stump, E., 1987, Construction of the Pacific margin of Gondwana during the Pannotios cycle, *in* McKenzie, G.D., ed., Gondwana Six: Structure, tectonics and geophysics: American Geophysical Union Monograph 40, p. 77–87.

Stump, E., and Fitzgerald, P.G., 1988, Field collecting for fission-track analysis of uplift history of the Scott Glacier area, Transantarctic Mountains: Antarctic Journal of the United States, v. 23, p. 12.

Stump, E., and Fitzgerald, P.G., 1992, Episodic uplift of the Transantarctic Mountains: Geology, v. 20, p. 161–164.

Stump, E., Smit, J.H., and Self, S., 1986, Timing of events during the late Proterozoic Beardmore orogeny, Antarctica: Geological evidence from the La Gorce Mountains: Geological Society of America Bulletin, v. 97, p. 953–965.

Stump, E., Miller, J.M.G., Korsch, R.J., and Edgerton, D.G., 1988, Diamictite from Nimrod Glacier area, Antarctica: Possible Proterozoic glaciation on the seventh continent: Geology, v. 16, p. 225–228.

Stump, E., Korsch, R.J., and Edgerton, D.C., 1991, The myth of the Beardmore and Nimrod Orogenies, *in* Thomson, M.R.A., Crame, J.A., and Thomson, J.W., eds., Geological evolution of Antarctica: Cambridge, England, Cambridge University Press, p. 143–147.

Vetter, U., Lenz, H., Kreuzer, H., and Besang, C., 1984, Pre-Ross granites at the Pacific margin of the Robertson Bay terrane, north Victoria Land, Antarctica: Geologisches Jahrbuch, v. B60, p. 363–369.

von der Borch, C.C., 1980, Evolution of late Proterozoic to early Paleozoic Adelaide foldbelt, Australia: Comparisons with post-Permian rifts and passive margins: Tectonophysics, v. 70, p. 115–134.

Wade, F.A., and Cathey, C.A., 1986, Geology of the Basement Complex, Western Queen Maud Mountains, Antarctica, *in* Turner, M.D., and Splettstoesser, J.F., eds., Geology of the central Transantarctic Mountains: American Geophysical Union, Antarctic Research Series, v. 36, p. 429–453.

Walker, N.W., and Goodge, J.W., 1991, Significance of Late Archean–Early Proterozoic U-Pb ages of individual Nimrod Group detrital zircons and Cambrian plutonism in the Miller Range, Transantarctic Mountains: Geological Society of America Abstracts with Programs, v. 23, no. 5, p. A306. ■

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