THE ROSS ACTIVE MARGIN OF ANTARCTICA

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Introduction: The period of Earth history spanning the late Proterozoic to early Paleozoic is marked by the breakup of one supercontinent, Rodinia, and the assembly of another, Gondwanaland. The rocks of the Ross orogen, exposed throughout the length of the Transantarctic Mountains, record the manifestations of this interval as they occurred along the Pacific margin of Antarctica. Proterozoic reconstructions juxtaposing western Canada and eastern Australia were extended to the southwestern United States and Antarctica by Moores (1991) in the so-called SWEAT hypothesis. Although the separation of Laurentia and eastern Gondwanaland during the Rodinia breakup has become a successful model for explaining the origin of the Pacific margins of both of these regions, the precise positioning of the continents prior to breakup and the timing of the separation itself continue to be uncertainties.

Rocks of the Ross orogen within the Transantarctic Mountains offer no evidence on which to pin a point on Laurentia. The only outcropping of cratonic rocks in the Transantarctic Mountains is the Nimrod Group in the Miller and Geologists Ranges, which has recently yielded U-Pb zircon data indicating initial magma generation at ca. 3 000 Ma, with subsequent high-temperature metamorphic and/or magmatic events at 1720 and 530 Ma (Goodge and Fanning, 1999). The basement to the Ross orogen throughout the Transantarctic Mountains, as determined by Nd model ages on early Paleozoic plutonic rocks, is primarily Mesoproterozoic continental crust, with some components on the outer portion of the belt ca. 1000 Ma, but whether any of this material is autochthonous with respect to the Antarctic craton, or was displaced in terranes during the development of the Ross orogen, as suggested by Borg and DePaolo (1994), remains uncertain.

The geology of specific sectors of the Transantarctic Mountains (Fig. 1) has been reasonably well known for several decades, and considerable advances have been made during that time in refining the geological history within them. However, correlation of sequences between the sectors continues to be problematic. The notion of terrane displacement during development of the Ross orogen offers a framework for future research aimed at resolving the differences between the various sectors.

Initial Sedimentation: By the end of the decade following the International Geophysical Year (IGY) it was generally thought that sedimentation throughout the Ross orogen began in the Neoproterozoic with widespread clastic units composed of graywacke and shale deposited in relatively deep water, and followed in the Early-Middle Cambrian with limestone deposition, in places associated with volcanism and clastic sedimentation. The "Neoproterozoic" units included the Robertson Bay Group, Wilson Group, and Priestley Formation in northern Victoria Land (NVL), Beardmore Group (Goldie Formation and the calcareous Cobham Formation) in the central Transantarctic Mountains (CTM), La Gorce Formation and Duncan Formation in the Queen Maud Mountains (QMM), and Patuxent Formation in the Pensacola Mountains (PM). This generalization has become a lesson in the hazards of trying to correlate unfossiliferous, nondescript clastic units. The Robertson Bay Group was found to contain uppermost Cambrian-Tremadocian fossils, lending support to the evolving concept of terranes in NVL (Bradshaw *et al.*, 1985). In the PM the Patuxent Formation occurs at two different localities. In the Neptune Range, where the Patuxent is not associated with volcanic rocks, its age is constrained by the unconformably overlying Middle Cambrian Nelson Limestone. To the west of the Neptune Range, however, in the Schmidt and Williams Hills, the Patuxent Formation is interbedded with basaltic lava flows and a rhyolite, U-Pb dated at 500 ± 8 Ma. Clearly the "Patuxent Formation" at these two localities is of different ages, and further, the folded clastic sequence in the Neptune Range is constrained only to be older than middle Middle Cambrian, and may in fact not be Neoproterozoic at all.

In the CTM the age of the Goldie Formation, as well as its relationship to the overlying Lower Cambrian Shackleton Limestone is controversial. Goldie Formation is exposed throughout a considerable area from north of Nimrod Glacier to south of Beardmore Glacier. At Cotton Plateau, at the cratonward (western) margin of its outcrop, Goldie sediments are associated with a pillow basalt and gabbro which has yielded a Sm-Nd mineral isochron of 762 ± 24 Ma (Borg *et al.*, 1990), and has been cited as possibly marking the time of breakup of Laurentia from Antarctica. This age is, however, at odds with detrital zircon ages as young as ca. 600 Ma from Goldie Formation collected at Kon-Tiki Nunatak and the Cobham Range, to the north and somewhat east along strike of Cotton Plateau. In the view of the author it is possible that the "Goldie Formation", as it is presently recognized, may in fact represent two sequences of different ages, like the "Patuxent Formation" in the Pensacola Mountains.

In southern Victoria Land (SVL) metasedimentary sequences are represented by the amphibolite-grade Koettlitz Group and the greenschist-grade Skelton Group. Both are characterized by considerable calcareous components, both have conglomerates and arenaceous units, and the Skelton Group has recognizable volcanics. Geologists who have worked on these rocks have typically shied away from actually correlating the two formations, but in the opinion of the author they are likely to be of the same cycle and basin of deposition due to their gross similarities in lithology and their spatial proximity. Over the years suggestions for correlation of these rocks beyond SVL have ranged from Cambrian calcareous sequences, to the Neoproterozoic Cobham Formation (Beardmore Group), to the Mesoproterozoic Nimrod Group. Two separate plutons which cross-cut folded Skelton Group have been U-Pb dated at 550 Ma, clearly constraining these rocks to be older than Cambrian (Rowell *et al.*, 1993; Encarnaci6n and Grunow, 1996). Further to this, a pillow basalt from the same sequence has yielded a Nd model age of 800-700 Ma, in a similar timeframe to the mafic rocks at Cotton Plateau. In summary, very limited age data on volcanism suggests that deposition in the Ross orogen had begun by 800-700 Ma, but that a considerable portion of what has been thought of as initial sedimentation was occurring near the end of the Neoproterozoic.

Tectonic activity began in some, if not all, of the Ross orogen during the latter part of the Neoproterozoic and continued through the Cambrian, culminating in widespread plutonism (collectively called the Granite Harbour Intrusives) throughout the Transantarctic Mountains in the Late Cambrian. Although the plutonism is likely indicative of rapid subduction along the entire belt (with exception perhaps of the PM), the sequence of events leading up to the plutonism varied between each of the sectors of the Transantarctic Mountains. Throughout the remainder of this presentation we will examine the histories of each sector in turn and make some suggestions to account for their disparities.

Northern Victoria Land: Since the 1980's it has been recognized that NVL is composed of three terranes separated by major faults. The western Wilson terrane (WT), by virtue of the presence of Granite Harbour Intrusives is linked to the rest of the Ross orogen, whereas the medial Bowers terrane (BT), and the eastern Robertson Bay terrane (RBT) are allocthonous, and contain elements found nowhere else in the Transantarctic Mountains. U-Pb zircon dating suggests that the metasediments in the western part of the WT were involved in a magmatic event around 544 Ma (Black and Sheraton, 1990), and also indicate their Precambrian age. In the Terra Nova Bay area a portion of the Priestley Formation has yielded fragments of body fossils indicative of a Paleozoic age. Overall however, the stratigraphy of the Wilson has not been integrated. Although models vary in detail, it is generally proposed that during the Cambrian subduction was occurring from the east beneath the WT, with collision of the BT and RBT around 500 Ma (e.g. Ricci *et al.*, 1997). The BT contains a primitive magmatic arc and overlying sediments containing Upper Cambrian fossils (unique within the Transantarctic Mountains).

Southern Victoria Land: The boundary between NVL and SVL is in the vicinity of David Glacier where the mountains narrow to a few tens of kilometers and are composed exclusively of Granite Harbour Intrusives. Because of the lack of exposures it may never be possible to link NVL and SVL in a geologically meaningful way. Farther south between Mackay and Skelton Glaciers the Koettlitz and Skelton Groups appear. These sequences are much more calcareous that the metasediments in NVL, but unfortunately although the Koettlitz Group shows considerable stratigraphic variation, what is tops in the sequence is unknown. As mentioned above there is evidence that the sequences had already been deformed and metamorphosed by 550 Ma. In fact it would appear that all sedimentation in SVL had ceased by the Cambrian. Deformation of the metamorphic sequences in SVL was complex and at least in some cases appears to have been controlled by syntectonic plutonism. The major plutonic bodies in the McMurdo Sound area are elongate in a NNW-SSE direction, suggesting compression from the ENE. The Bonney pluton, one of the older and largest in the area, has U-Pb and Pb-Pb dates ranging between 522 and 505 Ma (Encarnación and Grunow, 1996).

The geological boundary between SVL and the CTM is Byrd Glacier which separates regions of markedly different rocks. From south of Skelton Glacier to the Britannia Range the rocks are mostly Granite Harbour Intrusives, but in portions of the Britannia Range there is an amphibolite-grade assemblage of non-calcareous, schistose rocks called the Horney Formation. The unit is essentially unmapped and unstudied, so its age, lithology, and structural history remain to be determined, but from preliminary descriptions it appears not to be similar to the limestone or marble bearing sequences north of Skelton Glacier or south of Byrd Glacier.

Central Transantarctic Mountains: The oldest sedimentation in the Ross orogen in the CTM is that of the Beardmore Group, with the chronological constraints mention above. This is followed by deposition of the Lower Cambrian (Atdabanian-Botomian) Shackleton Limestone. At Cotton Plateau and several other localities to the north and east, its contact with Goldie Formation has been reported to be unconformable (Laird *et al.*, 1971). Rowell *et al.* (1986) have interpreted all of these contacts (except the one at Cotton Plateau, which they did not visit) to be faulted. Stump *et al.* (1991) affirmed the unconformable relationship at Cotton Plateau; however, others have recently suggested that the contact at this locality may too be faulted.p At issue is whether or not Goldie Formation was deformed before deposition of Shackleton Limestone. Even if the contacts between the two units are faulted, this does not preclude the possibility that folding of Goldie Formation occurred before deposition of the Shackleton. At the localities examined by Laird *et al.* (1971) and the author, the basal beds of the Shackleton are clastic, not calcareous, as might be expected in a transgressive sequence, and bedding in the overlying Shackleton parallels the contact with lower Goldie Formation which in the majority of cases is truncated at an angle at the contact.

Following its deposition the Shackleton Limestone was tightly folded. Throughout most of its outcrop the underlying Goldie Formation has had only one generation of folding recognized. Herein is a paradox given the apparently unconformable nature of the Shackleton over the Goldie. The most convincing locality where two generations of deformation are observed in Goldie Formation is at Cotton Plateau at the very western margin of its outcrop (Stump *et al.*, 1991). A model which has been proposed to resolve the paradox is that a terrane or microcontinent across which Goldie Formation was deposited collided obliquely with the Antarctic craton causing steeply plunging folds with cleavage in Goldie at Cotton Plateau, but in areas farther to the east the Goldie was only warped broadly, causing tilting and erosion of Goldie prior to deposition of Shackleton, but not recognizable mesostructures that became overprinted during deformation of the Shackleton (Stump *et al.*, 1999). This is linked to the oblique movement recorded in the Endurance shear zone in the Miller Range by Goodge et al. (1993). This model further accounts for the young (ca. 600 Ma) zircons in portions of the Goldie as coming from a volcanic source (Skelton Group) to the north of Byrd Glacier.

Following deformation of the Shackleton Limestone, conglomeratic and sandy units (Douglas Conglomerate, Starshot Formation) were deposited unconformably over the Shackleton, and then themselves caught up in folding. Clasts derived from the Shackleton, the Goldie, and from plutonic rocks are included in the Douglas. At present the plutonic rocks have not been dated, so the maximum age of the Douglas is constrained only to be younger than the Shackleton.

Queen Maud/Horlick Mountains: The last outcrops of Goldie Formation occur around Ramsay Glacier. The region beyond that in the QMM and Horlick Mountains holds some close similarities to the geology of the CTM, and some distinct differences. In the upper Scott and Reedy Glaciers area are occurrences of the La Gorce Formation which is closely similar to Goldie Formation. In the La Gorce Mountains deformation of La Gorce Formation produced steeply plunging folds and cleavage similar to the style of the older deformation recorded in Goldie Formation at Cotton Plateau. As in the CTM, the region from Shackleton to Reedy Glacier contains fossiliferous Cambrian limestone sequences, but here they range from Lower to Middle Cambrian in age (Encarnación *et al.*, 1999) and are associated with a voluminous bi-modal suite of volcanic rocks, together called the Liv Group. U-Pb zircon dating of Liv Group volcanics (including Wyatt Formation) has shown a spread in ages from ca. 526 Ma to 505 Ma (Encarnación and Grunow, 1996; Van Schmus *et al.*, 1997; Encarnación *et al.*, 1999). A hypabyssal phase of Wyatt Formation intrudes folded La Gorce Formation in the La Gorce Mountains, indicating that La Gorce folding was pre-526 Ma. Elsewhere in the La Gorce Mountains Wyatt Formation is faulted against La Gorce Formation, and throughout the Queen Maud Mountains Liv Group is severely deformed. The sequence of deformation in the CTM and the QMM appears to be the same, with Goldie and La Gorce Formations folded and cleaved along the cratonic margin of the orogen, prior to deposition and emplacement of the Lower Cambrian Shackleton Limestone and Liv Group, both subsequently deformed.

The fundamental difference between the CTM and the QMM is the presence of widespread bi-modal volcanism in the Liv Group. This may represent an episode of extension along the outer margin of the proposed terrane or microcontinent as oblique impingement ceased and before active subduction commenced outboard of the presently-exposed sequences. Alternatively, this volcanism may represent back-arc spreading during the initial stages of active subduction in this segment of the Transantarctic Mountains. U-Pb dating of early Granite Harbour Intrusives in the Scott Glacier area indicates emplacement around 521 Ma, and perhaps as early as 531 Ma (Encarnación and Grunow, 1996). It is perhaps notable that these ages are 15-20 m.y. younger than the ages of the oldest plutonic rocks in NVL and SVL, indicating perhaps that subduction had begun earlier in the Victoria Land sector than in the region to the south.

Thiel Mountains: The Thiel Mountains are separated widely from the Horlick Mountains and the PM by ice cover. The predominant unit is the Thiel Mountains Porphyry, a silicic, hypersthene-bearing porphyry similar in composition to the Wyatt Formation, suggesting similar incorporation of continental material in their formation. The age of the Thiel Mountains Porphyry and associated plutonic rocks, however, is around 502 Ma, considerably younger than at least the onset of magmatism in the Scott Glacier area (Pankhurst *et al.*, 1988). The porphyries, as well as an associated sedimentary section (Mt. Walcott Formation), are flat lying and apparently were not deformed. This may be because deformation had ceased elsewhere in the Ross orogen by the time of formation of these rocks, or alternatively that this area was too much on the craton and escaped deformation that effected more outboard portions of the belt.

Pensacola Mountains: Aspects of the geology of the PM have been mentioned above. The oldest unit is "Patuxent Formation" folded prior to deposition of overlying Middle Cambrian Nelson Limestone. It is tempting to relate this folding to that of the Goldie and La Gorce Formations, but the age constraint is Middle rather than Lower Cambrian. Early Cambrian limestones do occur in the Argentina Range, but they are isolated and show no contacts with other formations. The Nelson Limestone is overlain by volcanic and clastic rocks of the Gambacorta and Wiens Formations. These and the Nelson were broadly warped and eroded, but not deformed nearly so severely as the Cambrian sequences elsewhere in the Transantarctic Mountains (Storey *et al.*, 1996). Furthermore, known plutonism is restricted to one small occurrence. In addition, younger "Patuxent Formation" was being deposited around 505 Ma. The less intense deformation and minimal magmatism in this region may indicate that subduction was less active in this sector of the Transantarctic Mountains than elsewhere. One plate tectonic scenario which could account for such a situation is that this area was close to the pole of rotation of the converging Pacific and Antarctic plates with less closure occurring here than farther along the Transantarctic Mountains.

Conclusions: Several suggestions can be drawn from the foregoing discussion. 1) Although data is meager, deposition in the Ross orogen appears to have begun by around 750 Ma. 2) Deformation appears to have begun in the Victoria Land sector before ca. 550 Ma when the oldest plutonism is recorded. 3) Ages of detrital zircons in sediments of the Goldie indicate that deposition occurred south of Byrd Glacier till sometime after ca. 600 Ma. It is suggested that the source of these zircons was volcanic rocks in SVL. 4) Deformation of Goldie and La Gorce Formations focused in a zone of oblique convergence adjacent to the craton with only minor warping outboard of this region. 5) Erosion following this deformation occurred prior to deposition (and emplacement) of the Early Cambrian Shackleton Limestone (and Liv Group). 6) Extension produced the bi-modal volcanic suite of the Liv Group. 7) This period (Atdabanian-Botomian) marked a transition from one of oblique convergence to orthogonal subduction along the Transantarctic Mountains, as suggested by Encarnación and Grunow (1996). 8) Subsequent deformation affected rocks throughout the Transantarctic Mountains. 9) Widespread plutonism occurred during the waning stages of deformation and subsequent to it until ca. 500 Ma. 10) The diminishing intensity of both deformation and plutonism in the direction of the Pensacola Mountains may indicate that they we close to a pole of rotation for convergence between the Pacific and Antarctic plates.

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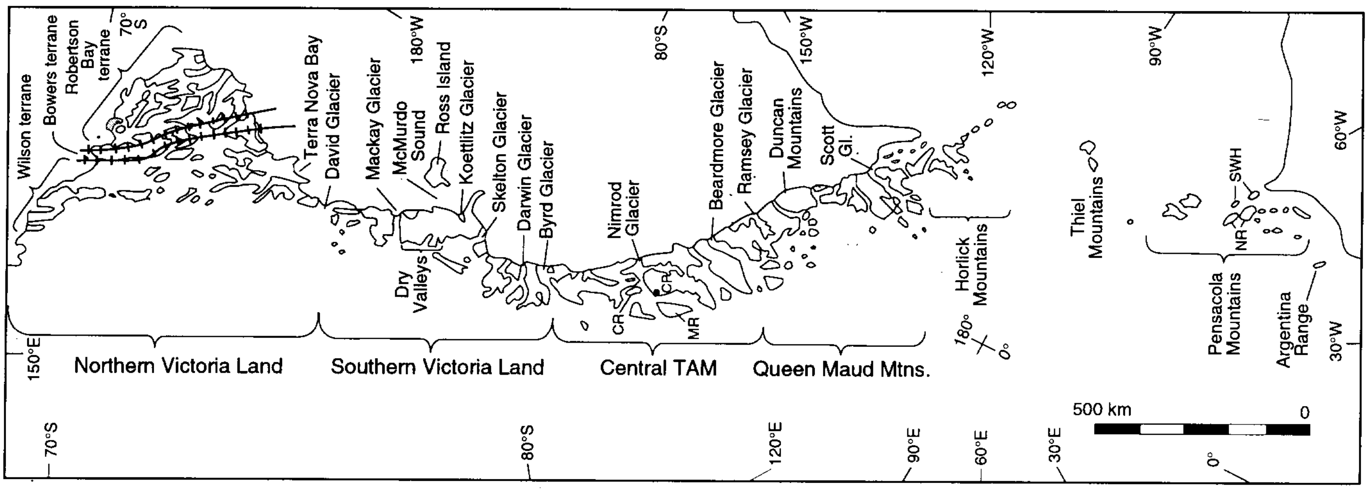

Figure 1. Location map for Transantarctic Mountains. CP = Cotton Plateau; CR = Cobham Range; MR = Miller Range; NR = Neptune Range; SWH = Schmidt and Williams Hills.