Changing magmatic and tectonic styles along the paleo-Pacific margin of Gondwana and the onset of early Paleozoic magmatism in Antarctica

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Abstract. Basement rocks of the Transantarctic Mountains are believed to record a change in the paleo-Pacific margin of Gondwana from a passive to a tectonically active margin. Widespread emplacement of calc-alkaline batholiths (Granite Harbor intrusives) occurred during the active margin phase. We present new concordant zircon and titanite U-Pb ages for these magmatic rocks in southern Victoria Land and the Scott Glacier area. Most magmatic rocks previously associated with a pre-late Early Cambrian (>530 Ma) deformational event(s) (Beardmore orogeny) have yielded younger crystallization ages. The lack of definite arc magmatism prior to ~530 Ma suggests that deformation may have been associated with a strike or oblique-slip regime, although shallow subduction without significant arc magmatism cannot be ruled out. Local transpressional and transtensional domains may account for compressional deformation and rare alkaline and carbonatite magmatism during this early period. The oldest and most voluminous magmatic rocks were emplaced after ~530 Ma. This magmatism has been associated with active subduction, and suggests a fundamental change in the plate boundary at ~530 Ma. Ductile shearing of plutons and contractional deformation of supracrustal rocks after ~530 Ma (Ross orogeny) may have been due to transpressional tectonics in an oblique subduction setting and/or a collision. Compressional deformation associated with the Ross orogeny may have ceased by ~500 Ma along the southern Victoria Land-Scott Glacier segment of the Antarctic margin, as indicated by undeformed magmatic rocks of this age, although magmatic activity continued to at least ~485 Ma.

Introduction

The Transantarctic Mountains (Figure 1) lie along the edge of cratonic East Antarctica, which was part of the paleo-Pacific margin of Gondwana in early Paleozoic time. Basement rocks exposed in the Transantarctic Mountains are inferred to record a phase of Proterozoic rifting and passive margin sedimentation, followed by a period(s) of deformation and magmatism that extended into the Ordovician [e.g., Borg et al., 1990; Moores, 1991; Dautel, 1991, 1992; Stump, 1992, 1995; Goode, 1995]. The magmatic rocks represent a continental margin arc that developed throughout the length of the Transantarctic Mountains. Here we report new zircon and titanite U-Pb ages that provide constraints on the time of emplacement of some of the oldest and most voluminous magmatic rocks in southern Victoria Land and the Scott Glacier area. Our investigation bears on the following questions: (1) Was there magmatism associated with pre-late Early Cambrian deformation along this segment of the Transantarctic Mountains? (2) If there was magmatism at this time, then in what types, volumes, and locations? The age of the earliest arc-related magmatic rocks provides a minimum date for when this margin of Gondwana may have converted to a subduction zone capable of generating a major magmatic arc. Recognizing the specific plate kinematic settings in which this margin evolved, and determining the precise timing of changes in settings, is important for developing models for the tectonic evolution of this part of the Gondwana margin and for understanding the specific roles that “Pan-African” mobile belts played in the assembly of Gondwana [e.g., Grunow et al., 1995].

Transantarctic Basement and Inferred Geologic Settings

The basement of the Transantarctic Mountains consists of all rock units that formed prior to a widespread mid-Paleozoic erosion surface (Kukri penplain). The erosional surface is overlain by Devonian to Triassic sedimentary sequences assigned to the Beacon Supergroup [Barrett, 1981]. The Beacon Supergroup is generally flat-lying from north Victoria Land to the Thiel Mountains, but is folded in the Pensacola Mountains (Figure 1) as a result of the Late Permian-Early Triassic Weddellian orogeny [Ford, 1972]. Basement units consist largely of low-grade metamorphosed Neoproterozoic carbonates, shallow water clastics (Skelton Group), and deeper water turbidites (Beardmore Group), and Cambrian limestone (Byrd Group) and volcanics [e.g., Rowell et al., 1992, 1993a, b; Stump, 1995]. High-grade schists, amphibolites and gneisses (Nimrod Group) arc found in the basement of the Miller Range (Figure 1) [Grindley and McDougall, 1969; Goode et al., 1993a].

Passive Margin Phase(?)

A passive margin setting for the Beardmore Group turbidites has been inferred on the basis of their quartzose character and the absence of rock fragments [Smit and Stump,
In the Scott Glacier area (Figure 1) Beardmore Group clastics (La Gorce Formation) are constrained only as pre-late Early Cambrian because they are intruded by a possible hypabyssal phase of Wyatt Formation volcanics [Stump et al., 1986] dated here at ~526 Ma (see later).

In the Neptunian Range of the Pensacola Mountains (Figure 1), turbidites mapped as part of the Beardmore Group (Patanxent Formation) actually include units of different ages. Turbidites in the eastern Neptunian Range yielded early Paleozoic fauna [Rowell et al., 1995] and ~500 Ma zircon U-Pb ages from interbedded volcanics [Millar and Storey, 1995]. In the western Neptunian Range they are constrained as pre-late Middle Cambrian (> ~520 Ma) because they are in angular unconformity beneath late Middle Cambrian carbonates [Rowell et al., 1992]. Unlike the older turbidites, the Ordovician clastics are associated with a bimodal volcanic suite [Storey et al., 1992] and represent a younger separate rifting episode [Millar and Storey, 1995].

**Tectonically Active Phase**

On the basis of the structural relations, degree of deformation and metamorphism, and previous isotopic dating, deformational and magmatic events recognized in the basement of the Transantarctic Mountains have traditionally been assigned to one of three tectonothermal episodes: the Precambrian Nimrod, Precambrian Beardmore, or Cambrian-Ordovician Ross orogeny [Grindley and McDougall, 1969]. These three orogenies were originally recognized and named for the structural relationships observed in basement units of the Miller Range-Nimrod Glacier area (Figure 1) in the central Transantarctic Mountains and have subsequently been correlated with deformational and magmatic events elsewhere in the Transantarctic Mountains. Work over the past few years, however, has shown that the concept of three distinct orogenies requires modification and/or reevaluation.

**Nimrod deformation.** The Nimrod orogeny was seen as a Precambrian event involving high-grade metamorphism and deformation of rocks in the Miller Range [Grindley and McDougall, 1969]. Detailed structural analysis indicates that Nimrod deformation occurred in an orogen-parallel, left-lateral transpressional regime (Miller Range shear zone) [Goodge et al., 1993a]. Early K-Ar work suggested that metamorphism of the Nimrod Group occurred at ~1000 Ma [Grindley and McDougall, 1969], but these dates were later demonstrated to have been compromised by extraneous Ar [Goodge and Dallmeyer, 1992]. Subsequently, the timing of high-grade metamorphism and deformation of the Nimrod Group was constrained by zircon and monazite U-Pb ages on syntectonic gneisses and schists at 541-521 Ma, and ending at ~515 Ma, the age of an undeformed cross-cutting pegmatite [Goodge et al., 1993b]. Thus, deformation and metamorphism of the Nimrod Group is not Precambrian, but instead is part of an Early Cambrian event (using the timescale of Bowring et al. [1993]) [Goodge et al., 1993b]. As such, Nimrod deformation possibly overlapped with Ross deformation (as expressed in folding of the late Early Cambrian Shackleton Limestone; see below), and might be termed “early Ross”.

**Beardmore deformation.** The Beardmore orogeny was defined in the Nimrod Glacier area (Figure 1) as the tectonic...
event that caused folding of Neoproterozoic turbidites belonging to the Beardmore Group (Goldie Formation), prior to the deposition of unconformably overlying late Early Cambrian carbonates (Shackleton Limestone) assigned to the Byrd Group [Laird et al., 1971; Stump, 1995, p. 142]. While the timing of Beardmore deformation in the Nimrod Glacier area is only constrained as pre-late Early Cambrian, it has generally been considered as Neoproterozoic largely on the basis of a tenuous correlation with poorly dated ~600 Ma magmatic rocks (e.g., Wyatt Formation) in the Scott Glacier area (see discussion by Stump et al. [1991]). As a result, there has been a tendency to attribute any possible Neoproterozoic magmatism and deformation, mostly folding and low-grade metamorphism of Beardmore Group clastics, to the “Beardmore orogeny.”

Ross deformation and Granite Harbor intrusives. Folding of the late Early Cambrian Shackleton Limestone is the archetypal expression of the Ross orogeny [Grindley and McDougall, 1969]. All of the basement units throughout the range are intruded by voluminous plutonic rocks assigned to the Granite Harbor Intrusive Complex [Gunn and Warren, 1962] (Figure 1). Previous whole rock Rb-Sr and K-Ar dates suggest that most of these basement magmatic rocks where emplaced, or at least their isotopic systems were reset, during the Cambrian-Ordovician [Faure et al., 1979] (and see summaries by Stump, 1995) suggesting a major thermal event that could have closely coincided with folding of the Shackleton Limestone, and hence with the Ross orogeny. However, the division of intrusives into deformed “pretectonic” and undeformed “posttectonic” suites, along with isotopic dates that suggested some of the pre-tectonic plutons are Neoproterozoic, has led to the contention that some of the Granite Harbor intrusives were associated with the earlier Beardmore orogeny [Deutsch and Grogl, 1966; Faure et al., 1979; Felder and Faure, 1979; Skinner, 1983; Felder and Faure, 1990].

A much younger suite of middle to late Devonian plutons (~350-380 Ma) are found only in northern Victoria Land [see Stump, 1995, p. 73]. These younger plutons are associated with accreted terranes in that area [e.g., Bradshaw et al., 1985; Kleinschmidt and Tessensohn, 1987] and are not covered in this paper.

Suspect terranes. A suggested disparity in tectonic setting between Lower to Middle Cambrian carbonates (e.g., Shackleton Limestone of the Byrd Group) lying on the craton side of the Transantarctic Mountains, and volcanic rocks (Liv Group) of broadly equivalent age lying outboard of the craton, led to the hypothesis that aspects of the Ross orogeny may be associated with displaced terranes along the craton margin [Rowell and Rees, 1989]. Identification of potential sutures at two locations marked by the presence of possible oceanic basalts [Borg et al., 1990; Borg and DePaolo, 1994], and the realization that high-grade rocks in the Miller Range were deformed in a sinistral transpressional regime with potentially large displacement [Goode et al., 1993a] provided further support for the possibility of displaced terranes. Borg and DePaolo [1994] argued that an improved match of basement Nd isotopic provinces between Antarctica and North America, assuming that Antarctica and North America were contiguous in the Neoproterozoic [Moores, 1991; Datziel, 1991], is consistent with left-lateral terrane displacements on the order of ~3000 kilometers along the Antarctic margin between ~760 Ma, when separation of the two continents presumably occurred, and generation of the Granite Harbor intrusives at ~500 Ma. In the context of these models, those Granite Harbor intrusives that were apparently Neoproterozoic have been used to suggest that terranes may have been accreted following subduction-related convergence and arc magmatism, prior to the Ross orogeny, thus accounting for the earlier Beardmore deformation [Borg and DePaolo, 1991].

Objectives, Sample Selection, and Methods

Distinguishing and understanding the tectonic setting(s) of the deformatonal events recorded in the Transantarctic Mountains basement has been hindered by the lack of precise emplacement ages for the magmatic rocks. Most of the previous Neoproterozoic dates are subject to one or more of the following problems: (1) they have large errors, making assignment to the Precambrian equivocal, (2) they are based on isotopic systems that may have been partially reset, (3) the isotopic systematics are not consistent with a closed and/or initially homogeneous isotopic system, as indicated, for example, by a large mean square of weighted deviates (MSWD) for Rb-Sr isochrons, (4) the isotopic systematics do not have a straightforward interpretation, as for example in discordant zircon U-Pb data with possibly both inheritance and Pb loss, [Deutsch and Grogl, 1966; Faure et al., 1979; Stump et al., 1986; Felder and Faure, 1990]. These problems have led some to doubt that late Precambrian magmatism accompanied the Beardmore orogeny [e.g., Stump et al., 1986; Findlay, 1990].

The primary objective of our work was to date by the U-Pb method what were thought to be the oldest magmatic rocks in the basement of the Transantarctic Mountains in order to provide precise age constraints on the timing of the earliest magmatism. Our samples come from southern Victoria Land and the Scott Glacier area (Figure 1), where abundant magmatic rocks have been mapped in more detail and have been the subject of geochemical studies, providing the basis for sample selection [Borg, 1983; Stump et al., 1986; Smillie, 1992; Allibone et al., 1993]. We concentrated on sampling rocks considered to be Neoproterozoic based on previous isotopic work. These are the Olympus Granite gneiss, granitic stocks in the Skelton-Cocks Glacier area, the Carlyn Granodiorite, Wyatt Formation volcanics, and the Lonely Ridge Granodiorite [Deutsch and Grogl, 1966; Faure et al., 1979; Felder and Faure, 1990; Rowell et al., 1993b] (Figures 2, 3, and 4). In addition to dating the magmatic rocks that previously yielded Neoproterozoic dates, we also dated some of the oldest plutons in the Scott Glacier area based on intrusive relations mapped by us, and by others [Stump et al., 1986]. In southern Victoria Land we also dated two typical “post-tectonic” plutons.

Almost all zircons analyzed were nonmagnetic, and most went through three stages of hand-picking: prior to air abrasion [Krogh, 1982], after air abrasion, and after weak acid washing prior to dissolution. Most, and possibly all samples, had discordant zircons with old xenocrystic cores,
but we were able to obtain concordant subpopulations by careful selection based on morphology and optical clarity. Other details of sample preparation, analysis and data reduction are given in Table 1 and footnotes therein. A list of samples, locations, and their inferred ages are given in Table 2.

Results and Comparison with Previous Dates

Southern Victoria Land

Bonney pluton/Olympus Granite gneiss. The exact outcrop and rock type that was sampled by Deutsch and Groger [1966] in Victoria valley, which yielded the date of 589 ± 13 Ma (recalculated by Skinner [1983]) is uncertain [Findlay, 1990], and therefore we cannot verify this date. Instead, we have used the pluton-specific mapping of Allibone et al. [1993] in the Granite Harbor-Koettlitz Glacier area that indicates the Bonney pluton (Figure 2) to be one of the oldest (and largest) plutons in the area. The Bonney pluton has gneissic border facies formed during syn-crystallization and postrcrystallization deformation [Cox, 1993], and it appears that the sample of Deutsch and Groger [1966] may have come from the northern end of the Bonney pluton (Figure 2).

Sample KL-1K is a biotite-rich quartz diorite taken from the southeast margin of the Bonney pluton along the ridge immediately south of Miers Valley (Figure 2). It is a more mafic phase that is gradational into a coarser, K-feldspar porphyryic variety more typical of the Bonney pluton. Three zircon fractions, of which two are concordant and one slightly discordant (most likely due to slight recent Pb-loss), have precise and indistinguishable 207Pb/206Pb ("Pb-Pb") ages with an error-weighted mean of 505 ± 2 Ma (2σ) (Figure 5a). A fourth fraction is also concordant, but with a different Pb-Pb age of 522 ± 3 Ma. Because Pb loss in zircon occur-
ring soon after crystallization (which would maintain apparent concordance) is unlikely, we interpret the Pb-Pb age of the younger concordant fractions (505 ± 2 Ma) as the final crystallization age of the sample, and the other concordant fraction as inherited from a slightly older (522 ± 3 Ma) zircon population. The basement in this area of southern Victoria Land is nearly all intrusive rock, and magmas may have been generated and emplaced, but then remobilized, mixed, or assimilated by later pulses of magmatism. The presence of the ~522 Ma magmatic zircon is significant because it indicates magmatic activity in this area was present at least that time. Consistent with these results are zircon U-Pb data reported by Parkinson [1994] that “indicate a range from 530-520 Ma” for the suite of older plutons in the area.

The 589 ± 13 Ma date of Deutsch and Groger [1966] (recalculated by Skinner [1983]) remains a problem. The date is a zircon U-Pb upper intercept age based on three discordant fractions. The ~589 Ma date is obtained assuming that (1) the zircons do not have any inheritance, and that (2) the three zircon fractions are discordant due to recent Pb loss alone. It is possible, but unlikely, that the granite gneiss does not have any inherited zircon (see Findlay [1991]). And since a large amount of zircon (several tens of thousands of grains for each fraction) was analyzed by Deutsch and Groger [1966], it would have been difficult to avoid xenocrystic zircons, if present. The relatively large uncertainties (±25 Ma) on the Pb-Pb ages precludes precise evaluation of the second assumption, which predicts a concordance in the Pb-Pb ages. Because (1) the ~589 Ma date rests on these possibly erroneous assumptions, (2) there is uncertainty in the sample site precluding verification of the date [Findlay, 1990; Allibone et al., 1993], and (3) it is likely that a facies of the Boushey Pluton [Allibone et al., 1993] was sampled, the ~589 Ma date should be treated with caution. This date cannot be used as a reliable constraint for the timing of magmatism in southern Victoria Land.

Granite, Skelton-Cocks Glacier area. Sample SK-1D comes from a small granite stock associated with quartz syenite in the Skelton-Cocks Glacier area [Rowell et al., 1993b] (Figure 3b). One zircon fraction is concordant and has a Pb-Pb age of 552 ± 6 Ma. Two other fractions are slightly discordant, apparently due to relatively recent Pb loss (Figure 5b). The upper intercept age calculated from the three fractions yields a more precise age at 551 ± 4 Ma, which is within uncertainty of the Pb-Pb age of the concordant fraction. A nearby quartz syenite stock ~1 kilometer away (Figure 3b) yielded an identical upper intercept zircon U-Pb age [Rowell et al., 1993b].

Brown Hills Pluton. Our mapping (Figure 3c) indicates that the Carlyon Granodiorite that was dated in a previous

Figure 3. (a) Map of Granite Harbor area showing location of sample GH-3A at Coulour Cliffs. The equigranular pink granite is a typical example of a “post-tectonic” pluton, because of the absence of evidence for postcrystallization compressional deformation. (b) Map of area at confluence of Skelton and Cocks Glaciers showing location of sample SK-1D (geology from Rees et al., 1981). The quartz syenite has a zircon U-Pb age [Rowell et al., 1993b] that is identical to the granite. Fold structures (not shown) representing at least two phases of folding in the country rock (Skelton Group) are truncated by the quartz syenite [Rees et al., 1981]. (c) Map of the Brown Hills area showing location of sample BH-2. Granodiorites in this area were previously mapped as Carlyon Granodiorite, Mt. Rich Granite, or Hope Granite [Haskell et al., 1965]. Our mapping indicates that most of the area is underlain by an equigranular titanite-bearing granite (shaded), which becomes porphyritic (crosses) and distinctly foliated (indicated by strike and dip symbols) along its western margins [Grunow and Encarnación, 1993]. We call this granodiorite the Brown Hills pluton.
study by the whole rock Rb-Sr method [Felder and Faure, 1990] at 568 ± 54 Ma is the same pluton that we sampled and which we call the Brown Hills pluton [Grunow and Encarnación, 1993]. Sample BH-2 is a titanite-bearing hornblende biotite granite from Cooper Nunatak in the Brown Hills area (Figure 3c). All three zircon fractions analyzed from this sample are discordant due to inheritance of old xenocrystic zircon with apparent ages of 2.2 to 2.4 Ga (Figure 5c). Fragments of large (a few millimeters in diameter) magmatic titanite from this sample yielded concordant data with Pb-Pb and 206Pb/238U ages of 515 ± 8 Ma and 518 ± 5 Ma, respectively. With an estimated closure T of ~600°C [Mezger, 1994], the titanite provides a good estimate for the time of final crystallization of the Brown Hills Pluton. The Pb-Pb age of 529 ± 6 Ma from the least discordant zircon fraction provides a reasonable upper limit for the age of the pluton. The titanite and zircon Pb-Pb ages are within uncertainty of the whole rock Rb-Sr age (568 ± 54 Ma) of Felder and Faure [1990], but the precisions on the U-Pb ages constrain the Brown Hills Pluton to be of Cambrian, rather than possibly Neoproterozoic age.

**Post-tectonic plutons.** The sample from Granite Harbor (Figures 2 and 3a), GH-3A, yielded three concordant zircon analyses (Figure 5d). Two other fractions appear to have suffered Pb-loss at ~75 Ma. The error-weighted mean Pb-Pb age of the three concordant fractions is 498 ± 4. A four point whole rock Rb-Sr isochron on samples from the northern side of Granite Harbor that we interpret as coming from the same pluton yielded an age of 478 ± 35 Ma (MSWD = 2.1) [Allibone et al., 1993], which is within uncertainty of the U-Pb age.

Sample VN-1G is a fine-grained plagioclase porphyry dike from the Vanda dike swarm [Allibone et al., 1993] that intrudes the Bonney pluton (Figure 2) near its eastern margin in Wright Valley. This sample yielded one zircon fraction that is discordant, possibly due to Pb loss, inheritance of much older zircon, or both (Figure 5e). Two other fractions are internally concordant, but have slightly different Pb-Pb ages. As discussed for sample KL-1K above, this is interpreted to be caused by mixing of zircon populations that are close in age, and therefore the younger concordant fraction at 484 ± 7 Ma is taken as being the best estimate of final crystallization.

**Scott Glacier Area**

**Lonely Ridge granodiorite.** The Lonely Ridge Granodiorite in the southwestern margin of the Nielsdson Plateau (Figure 4) is a typical "post-tectonic" pluton. Basement gran-
<table>
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<th>Pb, ppm</th>
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<tr>
<td>75-100 a s</td>
<td>32</td>
<td>198</td>
<td>18.3</td>
<td>678</td>
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<td>0.08512</td>
<td>0.6780 (1.11)</td>
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<td>Sample Type</td>
<td>wt. μg</td>
<td>U-ppm</td>
<td>Pb-ppm</td>
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<td>207Pb/235U</td>
<td>208Pb/232U</td>
<td>205Pb/204Pb</td>
</tr>
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<td>-------------</td>
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<tr>
<td>75-100 a f</td>
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<td>4481</td>
<td>0.063</td>
<td>0.08334</td>
<td>1.04</td>
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<td>75-100 a l</td>
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<td>9.46</td>
<td>8616</td>
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<td>0.08468</td>
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<tr>
<td>LGC 3A</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>100-150 as HF</td>
<td>144</td>
<td>215</td>
<td>19.0</td>
<td>7631</td>
<td>0.123</td>
<td>0.08722</td>
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</tr>
<tr>
<td>75-100 a l</td>
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<td>4116</td>
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<td>100-150 a l</td>
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<td>100-150 a f</td>
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<td>1954</td>
<td>0.086</td>
<td>0.08431</td>
<td>1.22</td>
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<tr>
<td>100-150 as HF</td>
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<td>165</td>
<td>16.0</td>
<td>3657</td>
<td>0.104</td>
<td>0.09613</td>
<td>1.05</td>
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<tr>
<td>75-100 l</td>
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<td>860</td>
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<td>LGC-5C</td>
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<tr>
<td>100-150 a f</td>
<td>31</td>
<td>126</td>
<td>11.5</td>
<td>416</td>
<td>0.159</td>
<td>0.08483</td>
<td>1.05</td>
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<tr>
<td>100-50 l f</td>
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<td>185</td>
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<td>1.04</td>
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<td>100-150 as HF</td>
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<td>180</td>
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<tr>
<td>75-100 u l</td>
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<tr>
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<td>2772</td>
<td>0.097</td>
<td>0.08430</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Analyses obtained at the University of Michigan. Procedures were similar to those described by Parrish et al. [1987].

1. All analyses are on zircons except T (titanite); size fraction is given in micrometers; s is alabrad; f is flat grains with simple prismatic forms; l is elongate to accicular grains with simple prismatic forms; s is short grains with higher order forms; t is crystal tips, clear and crack-free; s is crack-free undifferentiated fragments; HF is leached in HF prior to dissolution after Mathison [1994]; most zircons are nonmagnetic.

2. Uncertainty in weights is ± 2 micrograms (range).

3. Measured ratio corrected for spike and Pb fractionation.

4. Corrected for spike, fractionation at 0.13 ± 0.4% amu⁻¹ for U, and 0.11 ± 0.05% amu⁻¹ for Pb, initial Pb: 206Pb/204Pb = 18.4 ± 0.5, 207Pb/206Pb = 15.6 ± 0.1, 208Pb/204Pb = 39 ± 1 (initial Pb values measured from south Victoria 1 and granitoids and reported by Parkinton [1994]; uncertainties in initial Pb cover the range of reported values), blank: 20 ± 12 pg Pb and 10 pg U (the isotopic composition and absolute uncertainty at 95% confidence level of Pb blank based on three complete procedural blanks is 206Pb/204Pb = 19.4 ± 1.2, 207Pb/204Pb = 15.79 ± 0.13, 208Pb/204Pb = 39.0 ± 0.8, error correlation of blank 206Pb/204Pb 207Pb/204Pb 208Pb/204Pb = 0.5). 

5. Ages and errors were calculated using the method of Ludwig [1982, 1994] using decay constants λ234U = 1.5513 x 10⁻⁹ and λ238U = 9.8485 x 10⁻¹⁰ [Steiger and Jäger, 1977], and present 234U/238U = 137.88, and incorporating all uncertainties quoted above as well as uncertainties in the 206Pb/204Pb and 207Pb/204Pb ratios (0.5% and 0.06%, respectively) unrelated to within-run statistics and mass fractionation (variations in collector gain) and uncertainties in the U-Pb spike calibration. Absolute 2σ errors (in parentheses) on the 207Pb/206Pb ages are given for concordant analyses only.

ρ is error correlation for the Pb/U ratios.
### Table 2. Summary of New U-Pb Ages on Basement Migmatic Rocks From the Transantarctic Mountains

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Sample Description</th>
<th>Sample Location</th>
<th>Inferred Age and 2σ (Ma)</th>
<th>Basis for Age*</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH-3A</td>
<td>Pink biotite granite to quartz monzonitic</td>
<td>Culloir Cliffs, Granite Harbor, south Victoria Land</td>
<td>498 (±4)</td>
<td>Mean $^{207}$Pb/$^{206}$Pb age of three concordant zircon fractions</td>
</tr>
<tr>
<td>VN-1G</td>
<td>Plagioclase porphyry dike</td>
<td>Wright Valley, south Victoria Land</td>
<td>484 (±7)</td>
<td>$^{207}$Pb/$^{206}$Pb age of one concordant zircon fraction</td>
</tr>
<tr>
<td>KL-1K, Bonney pluton</td>
<td>Biotite quartz diorite</td>
<td>&quot;Miers Ridge&quot;, south Victoria Land</td>
<td>505 (±2)</td>
<td>Mean $^{207}$Pb/$^{206}$Pb age of 2 concordant and 1 near-concordant zircon fractions</td>
</tr>
<tr>
<td>SK-1D</td>
<td>Granite</td>
<td>Cocks-Skelton Glacier, south Victoria Land</td>
<td>551 (±4)</td>
<td>Upper intercept age of slightly discordant zircon array (due to Pb loss).</td>
</tr>
<tr>
<td>BH-2, Brown Hills pluton</td>
<td>Hornblende biotite granite</td>
<td>Cooper Nunatak, Brown Hills, south Victoria Land</td>
<td>515 (±8)</td>
<td>$^{207}$Pb/$^{206}$Pb age of concordant titanite</td>
</tr>
<tr>
<td>NIL-1, Lonely Ridge granodiorite</td>
<td>Foliated granodiorite</td>
<td>Lonely Ridge, Nilsen Plateau, Scott Glacier area</td>
<td>521 (±9)</td>
<td>$^{207}$Pb/$^{206}$Pb age of single concordant zircon fraction</td>
</tr>
<tr>
<td>BLK 3C, Zanuck granite</td>
<td>Kspar megacrystic granite</td>
<td>Mount. Gerdel, Scott Glacier area</td>
<td>521 (±2)</td>
<td>Mean $^{207}$Pb/$^{206}$Pb age of 2 concordant zircon fractions</td>
</tr>
<tr>
<td>LGC-3A</td>
<td>Hornblende biotite tonalite</td>
<td>Mt. Paine, La Goree Mts. Scott Glacier area</td>
<td>531 (+5/-50)</td>
<td>Lower intercept of discordant zircon array (due to inheritance).</td>
</tr>
<tr>
<td>LGC-5A, Wyatt Formation</td>
<td>Pyroclastic: ash flow tuff</td>
<td>Ackerman Ridge, La Goree Mts., Scott Glacier</td>
<td>526 (+2)</td>
<td>Mean $^{207}$Pb/$^{206}$Pb age of 3 concordant zircon fractions</td>
</tr>
<tr>
<td>LGC-5C, Ackerman Formation</td>
<td>Dacitic lava flow</td>
<td>Ackerman Ridge, La Goree Mts., Scott Glacier</td>
<td>524 (+2)</td>
<td>Mean $^{207}$Pb/$^{206}$Pb age of 4 concordant zircon fractions</td>
</tr>
</tbody>
</table>

*Mean $^{207}$Pb/$^{206}$Pb ages are inverse variance weighted means.

Toids on the western side of Nilsen Plateau are foliated, and have been metamorphosed at low-grade and experienced postcrystallization shearing that locally produced cataclastic fabrics [Eastin, 1970; Stump, 1985]. Sample NIL-1 was taken from the southern side of Lonely Ridge where the Lonely Ridge Granodiorite is extensively exposed [Eastin, 1970]. The sample has a penetrative ductile shear fabric. The sample yielded only a small amount of high-quality euhedral zircon and, therefore, only one analysis was obtained (on 12 grains) from the sample. The analysis yielded concordant results with Pb-Pb and $^{206}$Pb/$^{206}$U ages of 521 ± 9 Ma and 527 ± 6 Ma, respectively (Figure 5f), which constrain the emplacement of the Lonely Ridge Granodiorite to the Early-Middle Cambrian.

The previous whole rock Rb-Sr isochron age of 607 ± 13 Ma [Faure et al., 1979; age recalculated by Stump [1995] with $^{87}$Rb = 1.42 X 10$^{-11}$ y$^{-1}$) is much older than our zircon Pb-Pb age. Of seven whole rock samples analyzed in this previous study, only four gave a good isochron fit (MSWD = 0.02), with a small spread in $^{87}$Rb/$^{86}$Sr (1.05 to 1.95). Recalculation of the date using the data and errors by Eastin [1970] and the method of York [1969] (Ludwig, 1994) yields a similar date of 598 Ma, but a larger 2σ error of +260 Ma. While it is possible that the whole rock Rb-Sr system was not compromised since igneous crystallization, the uncertainty in the age appears to have been underestimated.

**Zanuck Granite, Scott Glacier area.** In the area east of Scott Glacier, from Price Bluff to Mt. Zanuck, we encountered at least four distinct intrusions based on cross-cutting relations. The oldest and one of the largest is a coarse, gray, K-feldspar megacrystic hornblende biotitic granitic to granodiorite named the Zanuck granite [Stump, 1985]. This pluton is well exposed in the Mt. Zanuck and Mt. Gerdel area, Price Bluff, and the adjacent nunataks northwest of Price Bluff (Figure 4). It intrudes the Wyatt formation (see below) at Hecimous Peak west of the Scott Glacier [Stump, 1995, p. 212]. The Zanuck Granite displays a distinct magmatic foliation, as well as a postcrystallization foliation and cataclastic fabric in some areas [Stump, 1995, p. 211]. Sample BLK-3C is Zanuck Granite taken from the southern slope of Mt. Gei-
Figure 5. Concordia diagrams [after Tera and Wasserburg, 1972] of U-Pb data on zircon and titanite from Table 1. All analyses are on zircon except as noted in Figure 5c. Abscissa and ordinate on all diagrams are $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$, respectively, as indicated in Figure 5a. Sample names and their inferred ages are indicated at lower left of each panel. The data points used for the inferred ages are shaded and are listed in Table 2. The dashed arrows in Figures 5c, 5h, 5i, and 5j are discordia lines through the inferred crystallization ages and single discordant data points that fall outside the figures. The apparent age of the xenocrystic components (upper intercept ages) on those data points are indicated. Dashed arrows in Figures 5b and 5d are Pb loss trajectories.

del (Figure 4). The two zircon fractions analyzed from this sample are both concordant with a Pb-Pb age of 521 ± 2 Ma (Figure 5g). This age is indistinguishable from that of the Lonely Ridge Granodiorite at 521 ± 9 Ma.

Tonalite, Mt. Paine. Sample LGC-3A is an equigranular hornblende biotite tonalite obtained from the western slope of Mt. Paine (Figure 4). This sample is the only one that did not yield any concordant analyses (Figure 5h). Three zircon fractions form a linear array with a lower intercept at ~531 and a large asymmetrical uncertainty of ±5/50 Ma. A few kilometers south of our sample site, what may be the same pluton is described as biotite granite, and was observed to
intrude the Wyatt Formation [Stump et al., 1986]. If we sampled the same pluton observed by Stump et al. [1986], then field relations and the age of the Wyatt Formation provide a better upper age limit for this pluton at 526 ± 2 Ma (see below).

**Volcanic rocks in upper Scott Glacier area.** The Wyatt Formation is exposed in the La Gorce Mountains, the Nilsen Plateau, and at nunataks between these areas (Figure 4). It is predominantly a massive pyroclastic unit of dacitic composition, and was probably emplaced as an ignimbrite sheet(s) during caldera-forming eruptions [Borg, 1980; Stump et al., 1986]. Sample LGC-5A is Wyatt Formation taken from the northeast side of Ackerman Ridge approximately 15 m below the contact of the Wyatt with the overlying Ackerman Formation (Figure 4). Two concordant and one nearly concordant zircon fractions (Figure 5a) have precise and indistinguishable Pb-Pb ages that have a mean of 526 ± 2 Ma, which we interpret as the emplacement age of the Wyatt Formation. A fourth concordant fraction has a slightly older Pb-Pb age (535 ± 7 Ma) and may come from a population of zircons that crystallized in slightly older magmatic rocks that were incorporated as lithic fragments during the eruption of the Wyatt Formation. The younger population at 526 ± 2 Ma also have been incorporated in a similar manner in which case 526 ± 2 is a maximum age for the Wyatt. A minimum age is set by the age of a lava flow in the overlying Ackerman Formation at 524 ± 2 Ma (see below). Hence, the Wyatt Formation is tightly constrained as forming between 526 ± 2 Ma and 524 ± 2 Ma.

Previous attempts at dating the Wyatt Formation using the whole rock Rb-Sr method produced dates with large errors and data arrays that did not form isochrons [Faure et al., 1979; Stump et al., 1986]. On the basis of similar petrography, in particular the presence of cordierite and hypersthene, the Wyatt Formation had been correlated with volcanics and shallow intrusives in the Thiel Mountains [Murphy, 1969; Ford and Himmellberg, 1976; Stump et al., 1986, Pankhurst et al., 1988, Stump, 1995 (Figure 1)]. Whole rock Rb-Sr dating of these units [Pankhurst et al., 1988] has yielded good results that correlate ages on the Thiel Mountains porphyry and dacite sills dated as 485 ± 11 (13 points; MSWD = 2.6) and 480 ± 18 (5 points; MSWD = 1.6). These ages and the U-Pb age of 526 ± 2 Ma on Wyatt Formation indicate that the Thiel Mountains magmatism occurred later than Wyatt volcanism in the Scott Glacier area.

The Ackerman Formation conformably overlies the Wyatt Formation and is in contact with La Gorce Formation turbidites (Beardmore Group) along a high angle fault [Stump et al., 1986] (Fig 4). It consists of shallow marine clastics with interbedded volcanics [Stump, 1983]. Sample LGC-3C is from the second volcanic unit mapped by Stump [1983] in the Ackerman Formation, taken ~300 m from the base of the formation. The base of the volcanic unit sampled contains clasts of the underlying siltstone and has a brecciated top, and is therefore probably a lava flow [Stump, 1983]. Four zircon fractions yielded concordant analyses with a mean Pb-Pb age of 524 ± 2 Ma (Figure 5a), which we take as the emplacement age of the lava flow and the time of deposition of this part of the Ackerman Formation.

**Inherited Zircons**

Along with the predominantly concordant analyses that we used to infer the emplacement ages of the samples (Table 2), some of the zircon analyses were strongly discordant. These are clearly due to inheritance of old xenocrystic zircon (Table 1 and Figure 5). No precise age data can be extracted from these analyses, and the inherited zircons are possibly mixtures of several populations. Nevertheless, samples from the Scott Glacier area (Figures 5h-5j) have inherited zircons with apparent ages (0.9 Ga to 1.8 Ga) that are broadly consistent with lower crustal depleted mantle Nd model ages expected for the Scott Glacier area (1.1 Ga to 1.9 Ga) [Borg and DePaolo, 1994]. The apparent ages of inherited zircon in the Brown Hills pluton (2.2 Ga to 2.4 Ga) in southern Victoria Land are older than the Nd model ages for that area (1.7 Ga to 1.9 Ga) [Borg and DePaolo, 1994]. This discrepancy may be due to significant Pb loss in these inherited zircons which would lead to an apparently older upper intercept age.

**Discussion**

All the new ages obtained from the older granitoids and volcanic units in southern Victoria Land and the Scott Glacier area indicate that widespread magmatic activity commenced by at least the late Early Cambrian (~530 Ma). Similar U-Pb ages of 520-500 Ma have been reported for granitoids from the area east of the Miller Range between our two study areas (J. Mattinson, unpublished data, 1988, cited by Borg et al. [1990]). Figure 6 summarizes the new data and compares the timing of magmatism with other tectono-thermal events along the same sector.

Using a recently proposed timescale for the Cambrian [Bowring et al., 1993], deposition of the late Early Cambrian Shackleton Limestone in the Nimrod Glacier area coincided with voluminous arc magmatism in southern Victoria Land and the Scott Glacier area at ~530-520 Ma. This provides a useful time boundary for discussing deformational and magmatic events because deposition of Shackleton Limestone (and the apparent onset of widespread arc-related magmatism) separates Beardmore deformation from Ross deformation, as defined earlier (Figure 6). In the succeeding discussion we will call pre-late Early Cambrian deformation as simply "pre-530 Ma" deformation. This encompasses early Cambrian and Neoproterozoic deformational and magmatic events traditionally assigned to the Beardmore orogeny [Grindley and McDougall, 1969] and events that might be termed "early Ross", such as Early Cambrian displacements on the Miller Range shear zone [Goodge et al., 1993b].

The Beardmore Orogeny and Pre-530 Ma Magmatism

In addition to folding of Beardmore Group rocks (Goldie Formation) in the Nimrod Glacier area [Grindley and McDougall, 1969; Laird et al., 1971; Stump et al., 1991], there is evidence for pre-530 Ma tectono-thermal events elsewhere in the Transantarctic basement. In the Skelton-Cocks Glacier area of southern Victoria Land, two generations of folds in deformed Skelton Group metasediments are truncated by a quartz syenite stock dated by zircon U-Pb at 551 ± 4
Figure 6. Summary of new concordant zircon U-Pb age determinations (filled squares with ±2σ error bars) on basement magmatic rocks in southern Victoria Land and the Scott Glacier area. Data points in boxes are from magmatic units having evidence for post crystallization deformation; those without boxes are undeformed “post-tectonic” plutons. Data from the same sample are aligned along the vertical axis (compare with Figure 5). A major change along the southern Victoria Land-Scott Glacier sector of the paleo-Pacific margin of Gondwana is inferred at ~540-530 Ma after widespread emplacement of calc-alkaline batholiths commenced. Compressional deformation associated with the Ross orogeny may have ended by ~500 Ma as suggested by ages on “post-tectonic” plutons and the presence of essentially flat lying volcanioclastics in the Thiel Mountains (Figure 1) dated at ~500 Ma [Pankhurst et al., 1988]. Circle with error bars at lower left is for a carbonatite dike dated by Hall et al. [1995] as reinterpreted here. Age of the Shackleton Limestone is from Rowell et al. [1992]. The Miller Range shear zone was active by at least ~541 Ma and ended by ~515 Ma [Goode et al., 1993b]. Time of deposition of Goldie Formation is from Borg et al. [1990]. Geologic time scale from Bowring et al. [1993]. See text for further details.

(Figure 3b) [Rees et al., 1989; Kowell et al., 1993b]. In the Miller Range, left-lateral shear displacements and high-grade metamorphism of the Nimrod Group were occurring by at least ~541 Ma [Goode et al., 1993a]. In the La Gorce Mountains, Scott Glacier area, folding and low-grade metamorphism of Beardmore Group sediments (La Gorce Formation) was also probably pre-530 Ma because they are intruded by what is interpreted to be a hypabyssal phase of Wyatt Formation [Stump et al., 1986] dated here at 526 ± 2 Ma. On different grounds, as discussed in an earlier section, Borg and DePaolo [1994] argued for left-lateral terrane displacements on the order of ~3000 kilometers along the Antarctic margin between ~760 Ma and ~500 Ma.

All of the foregoing imply Neoproterozoic-Early Cambrian deformation (Beardmore orogeny in the loose sense), which occurred prior to post-Early Cambrian Ross deformation and magmatism. Folding of the Skelton Group is the only deformational event that is certainly Neoproterozoic [Kowell et al., 1993b]. Because of the uncertainty in the ages of deposition and deformation of Beardmore Group clastics, all these turbidites could have been deformed during the same Neoproterozoic event that folded the Skelton Group. Alternatively, Beardmore Group clastics may have been deformed at different times in different places. For example, in the Nimrod Glacier area, deformation of Beardmore Group clastics (Goldie Formation) may have coincided with Early Cam-
brian displacements along the Miller Range shear zone [Stump et al., 1991; Goodge et al., 1993a].

The few demonstrable examples of pre-530 Ma magmatic activity are of small volume, are alkaline and/or carbonatitic, or involve high-grade metamorphism. Syntectonic orthogneisses in the Miller Range shear zone yielded concordant or near-concordant zircon and monazite U-Pb ages of 541 to 521 Ma [Goodge et al., 1993b]. The Miller Range shear zone rocks were formed under high-grade metamorphic conditions (P>8 kbar; T = ~700°C) in a sinistral transpressional regime [Goodge et al., 1993a], and it is uncertain whether the orthogneisses protoliths were products of arc magmatism.

The small granitic stock in the Skelton-Cocks glacier area that we dated (Figure 3b) occurs adjacent to a quartz syenite that yielded an identical zircon U-Pb age of 551 ± 4 Ma [Rowell et al., 1993b]. Another alkaline intrusion of nepheline syenite occurs in southern Victoria Land at Radian Ridge (Figure 2) and is associated with a carbonatite dike [Hall et al., 1995; Wortley et al., 1995]. Fragments of a single zircon grain from the carbonatite yielded four internally concordant U-Pb analyses that plotted separately along concordia with Pb-Pb ages from 539 ± 5 Ma to 526 ± 4 Ma [Hall et al., 1995]. A possible interpretation of these data is that earlier carbonatite and alkaline magmatism, and growth of the oldest concordant zircon fraction, occurred at ~539 Ma. This was followed by recrystallization of the carbonatite with renewed growth of zircon at ~526 Ma caused by, and coincident with, emplacement of some of the large calc-alkaline plutons in the area. This suggestion is consistent with field relations, because the host nepheline syenite is tectonically foliated and the cross-cutting carbonatite dike is undeformed [Hall et al., 1995]. The older concordant fraction of the Bonney pluton dated here is 522 ± 3 Ma (Figure 5c) indicating that magmatism associated with the larger more abundant calc-alkaline plutons [Smillie, 1992] had begun by then. If so, the initial generation of alkaline and carbonatite magmas occurred prior to emplacement of the abundant arc-related plutons.

Attributing the early phase of deformation (pre-530 Ma) in the southern Victoria Land-Scott Gneissic sector to orogen-parallel strike-slip tectonics has merits, because such a scenario can account for (1) the absence of any known large volumes of arc magmas, (2) local compressional regimes under which some basement units may have been deformed, hence accounting for the “Beardmore orogeny”, (3) local extensional regimes where alkaline and carbonatite magmatism may occur, and (4) the elongation and inferred ~3000 kilometers of displacement of lower crustal Nd isotope provinces parallel to the Transantarctic Mountains [Borg et al., 1994]. It also could provide a major tectonic discontinuity along which later subduction may initiate. Such a strike-slip tectonic regime, perhaps along a highly oblique zone of convergence, occurring prior to ~530 Ma, is also consistent with structural and geochronologic data indicating orogen-parallel left lateral strike-slip displacements in the Miller Range beginning by at least ~541 Ma [Goodge et al., 1993a].

Although a strike-slip regime may provide an adequate model for the tectonic evolution of the southern Victoria Land-Scott Glacier sector in post-Beardmore Group, pre-Granite Harbor intrusives time (~730 Ma to ~530 Ma), the presence of subduction cannot be definitely ruled out. If subduction was present, the apparent absence of arc magmatism would suggest that, (1) the angle of subduction was shallow, similar to the nonvolcanic sections along the present Andean convergent margin [e.g., Jordan et al., 1983]. However, subduction would have to have been shallow for ~2000 kilometers along the southern Victoria Land-Scott Glacier sector, and unlike the Andean analogy where previous magmatism is known to have occurred along the apparently transient shallow subducting sectors, there is no known large volumes of pre-530 Ma magmatism along the Antarctic margin; (2) subduction was highly oblique, as in the northwest ern end of the Java trench [e.g., Currau et al., 1979]; and/or (3) subduction of only narrow marginal basins was involved. Indeed, the length of the orogen and the time period involved make it unlikely that deformational styles and any magmatism along the orogen remained uniform in time or space [e.g., Goodge and Dallmeyer, 1986]. Detailed structural mapping and geochronologic data on pre-Granite Harbor intrusive basement units is needed to fully understand the pre ~530 Ma phase of deformation.

In summary, although there is strong evidence for pre-530 Ma contractional and/or transpressional deformation of basement units at various locations throughout the Transantarctic Mountains, given the new data, there is at present only known large volume magmatism that accompanied these early deformational events. A strike-slip regime, perhaps along a highly oblique margin of convergence, can be invoked to account for deformation, but shallow subduction, with or without collisions, cannot be ruled out.

Subduction, Widespread Magmatism, and Ross Deformation

The pre-late Early Cambrian (>530 Ma) deformation phase(s) was followed by widespread emplacement of the Granite Harbor intrusives and eruption of volcanics. Development of this magmatic belt is a unifying feature along the Transantarctic Mountains basement (Figure 1). This magmatic belt is generally believed to have formed above a subduction zone dipping beneath the East Antarctic craton on the basis of (1) the linear nature of the magmatic belt, (2) the occurrence of a calc-alkaline suite of rock types ranging from gabbro to granite, but dominated by intermediate to silicic members, (3) regional variations in major and trace elements, and isotopic composition of the magmatic rocks resembling younger subduction-related magmatic belts, and (4) east-vergence structures in north Victoria Land consistent with westward subduction beneath the East Antarctic craton prior to collision of terranes there [Elliott, 1977; Borg, 1980; Borg, 1983; Bradshaw et al., 1985; Stump et al., 1986; Kleinschmidt and Tessonsohn, 1987; Borg et al., 1990; Smillie, 1992; Goodge et al., 1993a; Alibone et al., 1993]. Although the magmatic arc of this convergent margin is well-defined, assemblages representing the forearc appear to be missing along the southern Victoria Land-Scott Glacier sector. Granite Harbor intrusives are found across the width of the Transantarctic Mountains and the forearc may have been
removed by later Mesozoic-Cenozoic rifting along the mountain belt [Wilson, 1992] and might now be found in West Antarctica [e.g., Adams, 1986].

The development of this magmatic arc must reflect a fundamental change in the plate margin at this time. Subduction may have commenced, plate motions may have changed to less oblique convergence, or the angle of subduction increased. A component of orogen-parallel movement remained after the inferred change as suggested by the left lateral displacements along the Miller Range shear zone which was active until ~521 Ma (Figures 6 and 7) [Goodge et al., 1993a].

Orogen-normal folding of the Shackleton Limestone (Ross deformation) in the Nimrod Glacier area and contractual deformation of other supracrustal sequences such as the Ackerman and Wyatt Formations in the Scott Glacier area [Stump et al., 1986], as well as ductile and brittle shearing of plutons may all have occurred in the interval ~521 to ~500 Ma. The apparent absence of compressional shear zones in the younger post-tectonic plutons in southern Victoria Land (this paper) [Gunner and Martinson, 1975], and in the Scott Glacier area [van Schmus et al., 1995] dated at <500 Ma suggest that compressional deformation associated with the Ross orogeny may have been over by the early Ordovician in those sectors of the Transantarctic Mountains. Although caution should be exercised in concluding that apparently undeformed plutons are post-tectonic [Paterson et al., 1989], the assertion

![Figure 7. Schematic tectonic model for the south Victoria Land-Scott Glacier sector (Transantarctic Mountains) of the paleo-Pacific margin of Gondwana. The lack of any known large volumes of arc-related magmatism prior to ~530 Ma (Figure 7a) suggests that the tectonic regime may have been dominated by margin parallel displacements with possible terrane motion along the margin [e.g., Rowell and Rees. 1989: Borz and DePaolo, 1994]. Compressional deformation ("Beardmore orogeny") of the Skelton Group (SG), Goldic Formation (GF) and La Gorce Formation (LG), and rare alkaline and carbonatite magmatism (stars) during this period may have resulted from local transpressional and transtensional regimes, respectively. A major change in the type of plate boundary (strike/oblique-slip to convergent) or plate boundary characteristic (oblique to less oblique subduction; shallow to steeper subduction) occurs during the period ~540-530 Ma followed by the emplacement of widespread and abundant arc mafic rocks along the margin (GII, solid areas in Figure 7b). Deformation of these magmatic rocks and the Byrd Group (BG) ("Ross deformation") may have been associated with wrench faulting, or may have been caused by a collision of a terrane. Early Cambrian reconstruction of Gondwana is based on Grunow [1995]; sinistral shear zone in Miller Range is from Goodge et al. [1993a]; dominant fold trends are from Stump et al. [1986; 1991] and Rees et al. [1989]. The right border of the lightly shaded region in panels A and B is the present coastline (see Figure 1) and is not meant to mark the extent of East Antarctic continental crust. Compare with Figures 1 and 6, and see text for additional discussion.]}
that the <500 Ma plutons were emplaced after regional compressional deformation is consistent with the presence of essentially flat-lying ~500 Ma volcaniclastics in the Thiel Mountains (Figure 1) east of the Scott Glacier area [Pankhurst et al., 1988].

The cause of Ross compressional deformation(s) along the southern Victoria Land-Scott Glacier transect remains poorly understood. Many arcs are extensional [e.g., Edelman, 1991; Hamilton, 1995], and the large volumes of granitic magma emplaced in the Transantarctic basement, especially in the Scott Glacier area, imply dilation of the crust. Local contraction of supracrustal sequences may have occurred adjacent to wrench faults developed in an oblique subduction setting. Alternatively, collision of a terrane, as in northern Victoria Land [Kleienschmid and Tessensohn, 1987], outboard of the present area of exposure, may have caused Ross deformation after emplacement of the pretertiary plutons (Figure 7). Such a collisional scenario would suggest that convergence and deformation may possibly have continued further outboard following cessation of deformation at ~500 Ma in the present study area. Once again, detailed structural mapping, additional geochronologic data, and geophysical data are required to resolve these issues.

Conclusions

From the new U-Pb ages determined on magmatic rocks in the basement of the southern Victoria Land and the Scott Glacier area, and from previous work, the following conclusions are drawn:

1. All large volume plutonic and volcanic rocks that previously yielded Neoproterozoic ages (including the Bonney pluton/Olympus Granite gneiss(?), the Carlyon (granodiorite), the Wyatt Formation, and the Lonely Ridge granodiorite) are now constrained as late Early Cambrian, or younger (<530 Ma). Therefore, at present, there is no known large volume of possible arc-related magmatism that may have been related to pre-late Early Cambrian (>530 Ma) "Beardmore" deformation along this segment of the Transantarctic Mountains.

2. We reconfirm the presence of latest Neoproterozoic magmatic activity (~551 Ma) in southern Victoria Land [Rowell et al., 1993b]. This small volume alkali magma is not as easily related to subduction as the later (post ~530 Ma) large volume calc-alkaline magmatism.

3. Folding of the supracrustal rocks (Skelton Group) that are truncated by the ~551 Ma stocks is the only certain Neoproterozoic contractional deformation event along the south Victoria Land Scott Glacier area margin [Rees et al., 1989; Rowell et al., 1993b]. The folding of Beardmore Group clastics may have been associated with the same Neoproterozoic deformational event, but is not required by present age data. Beardmore Group clastics may have been deformed at different times in different areas.

4. The transition of the paleo-Pacific margin of this sector of Gondwana from a largely amagmatic yet tectonically dynamic margin, to an active subduction-related magmatic arc after ~530 Ma must reflect a fundamental change in the type of plate boundary (i.e., strike or oblique slip to convergent), or plate boundary parameter (e.g., shallow to steeper subduction; highly oblique to less oblique subduction). Although an overall strike-slip regime provides a reasonable setting for ~530 Ma magmatism and deformation, detailed petrologic, structural, and geochronologic work on pre-Granite Harbor intrusives basement is required to evaluate the possible nature and cause of the transition.

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