Age and Provenance of the Beardmore Group, Antarctica: Constraints on Rodinia Supercontinent Breakup

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ABSTRACT

New U-Pb ages for detrital and igneous zircons constrain the depositional age and sedimentary provenance of the Beardmore Group, a siliciclastic succession that records transformation of the East Antarctic margin during Rodinia breakup and subsequent Gondwana amalgamation. We divide rocks previously mapped as the Beardmore Group into (1) an inboard late Neoproterozoic assemblage (probably ≤670 Ma) and (2) a volumetrically dominant, outboard assemblage that is latest Early Cambrian or younger (≤520 Ma). The inboard assemblage contains mature, multicycle sediment derived from mixed cratonic sources dominated by 2.8- and 1.9–1.4-Ga components. It was deposited in a platformal-to-shoreline setting along an existing rifted margin. A new zircon age of 668 ± 1 Ma for mafic igneous rocks within this assemblage is younger than previously reported, indicating deposition in the late Neoproterozoic and raising questions as to the age of rifting. The outboard assemblage contains first-cycle sediment with dramatically different provenance, including fresh, young (580–520 Ma), locally derived igneous material and contributions from ~1400-, 1100–940-, and ~825-Ma sources. The youngest zircon ages (525–522 Ma) are consistent with newly discovered Cambrian-aspect trace fossils. Therefore, these outboard rocks are best considered as siliciclastic units of the upper Byrd Group. The detrital age patterns suggest a change from passive-margin sedimentation derived from the adjacent craton to a younger succession receiving detritus from an active-margin igneous source. Unique ~1.4-Ga age components, unknown in Antarctic and Australian cratons, coupled with eastward paleocurrents in the outboard assemblage, indicate that the ~1.4-Ga Laurentian anorogenic igneous province may extend beneath the polar ice cap in Antarctica. Together, the new age data support a Rodinia fit between Antarctica and Laurentia and suggest that sedimentation across the rifted margin was substantially younger than previously inferred.

Introduction

Neoproterozoic to lower Paleozoic craton-margin sedimentary successions provide detailed records of sedimentation patterns, sea-level fluctuations, faunal distributions, and postdepositional tectonism related to the breakup of Rodinia and subsequent Gondwana amalgamation. These successions, notably in western and eastern Laurentia, northeastern Asia, southern Africa, eastern Australia, and the Ross margin of Antarctica, provide paleogeographic and paleoclimatic details about a critical period of Earth history. The Beardmore Group in the Transantarctic Mountains of Antarctica (fig. 1) represents a significant element in the late Neoproterozoic to early Paleozoic evolution of the East Antarctic craton, such that its depositional history and provenance may help clarify paleogeographic relationships during the supercontinent transformations noted above.

The Beardmore Group is a thick assemblage of sandstone, shale, carbonate, and minor volcanic rocks mapped from Byrd Glacier to south of Beardmore Glacier (fig. 1) and correlated with similar siliciclastic units in the Transantarctic Mountains

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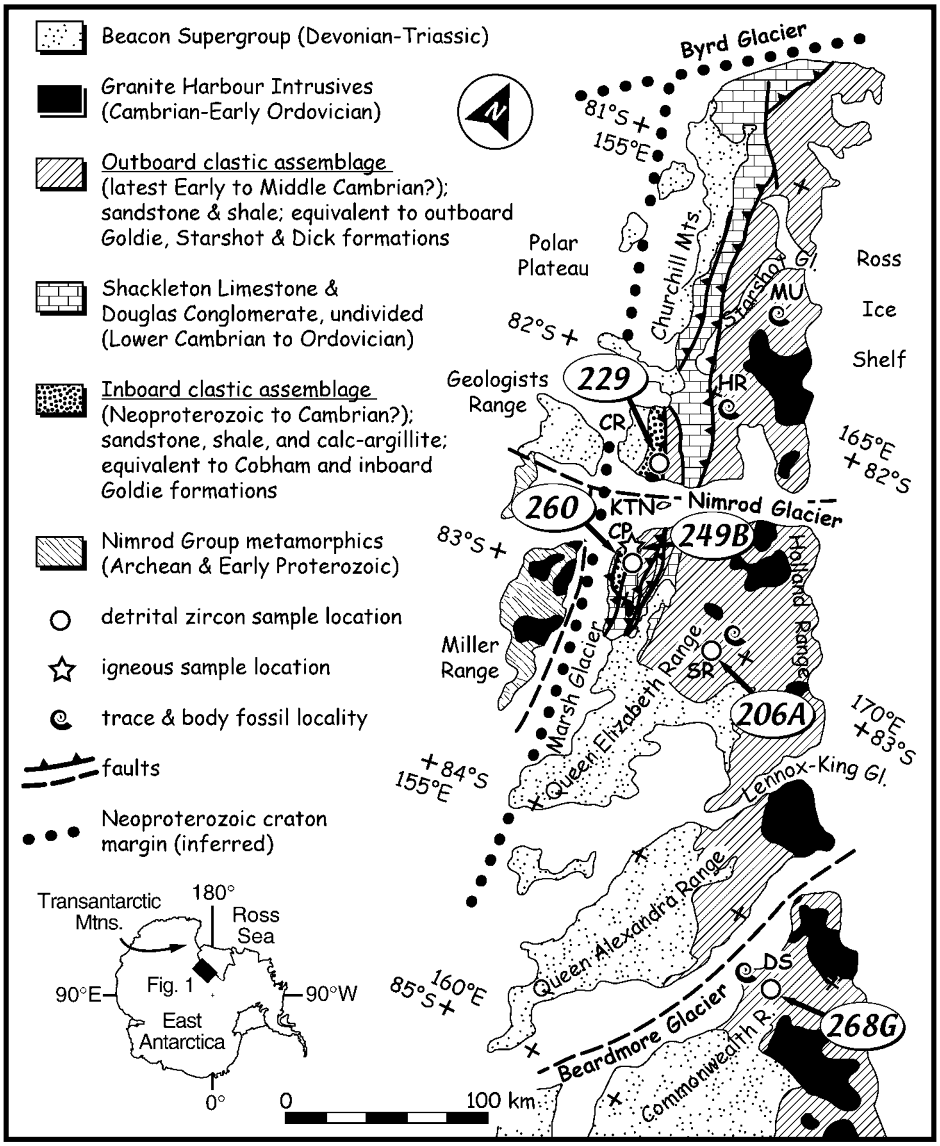


Figure 1. General geology of the central Transantarctic Mountains between Byrd and Beardmore glaciers, showing locations of dated samples. Inset shows location in Antarctica. Beardmore Group is divided into two depositional assemblages, inboard and outboard, based on geographic position, sedimentary petrology, depositional age, and inferred provenance: (1) inboard assemblage of sandstone, shale, and calcareous argillite, equivalent to the Cobham Formation and Goldie Formation at Cotton Plateau (*CP*); and (2) outboard assemblage of fine sandstone and shale, equivalent to widespread outboard Goldie, Starshot, and Dick Formations. Other localities include *CR*, Cobham Range; *DS*, Dolphin Spur; *HR*, Holyoake Range; *MU*, Mt. Ubique; and *SR*, Softbed Ridges.

(Schmidt et al. 1965; Stump 1982, 1995; Stump et al. 1986; Storey et al. 1992; Rowell et al. 2001). It is generally considered to be an unfossiliferous, lithologically monotonous succession of fine-grained siliciclastic rocks (Grindley and Warren 1964) that is in uncertain depositional relationship with underlying and overlying units. It is certainly younger than the crystalline basement of the East Antarctic Shield (represented by the Archean and Paleoproterozoic Nimrod Group to the west), and some have suggested that it is allochthonous with respect to the cratonic margin (Rowell and Rees 1989; Borg et al. 1990; Encarnación and Grunow 1996). Laird et al. (1971) concluded that the Beardmore Group is unconformably overlain by the Lower Cambrian Shackleton Limestone of the Byrd Group. Although this relationship has been questioned (Rowell et al. 1986; Goodge 1997), many have suggested a Neoproterozoic depositional age for the group (Laird et al. 1971; Laird 1981; Laird and Bradshaw 1982; Stump 1982, 1995). This assertion is supported by a Sm-Nd isotopic age of 762 ± 24 Ma for associated mafic volcanic rocks of purported rift origin (Borg et al. 1990). The Beardmore Group thus appears to record late Proterozoic breakup along the East Antarctic margin.

In this article, we present new U-Pb geochronologic data that constrain the depositional age and provenance of the Beardmore Group. We dated large populations of detrital zircon from several samples of sandstone by SHRIMP ion microprobe. In addition, by isotope dilution/thermal-ionization mass spectrometry (ID/TIMS), we determined a zircon age for mafic igneous rocks contemporaneous with the succession. Using these data, we show that rocks mapped as the Beardmore Group comprise two distinct assemblages of late Neoproterozoic and latest Early Cambrian or younger age. These results bear significantly on the timing and nature of the relevant conjugate rift margins during Rodinia breakup.

Beardmore Group

The Beardmore Group is held to be a thin, Neoproterozoic craton-margin succession that passes upward into thick flysch deposits consisting of turbidites and hemipelagic shale. It is divided into two units, the lower Cobham Formation (Laird et al. 1971) and the conformably overlying Goldie Formation (Gunn and Walcott 1962). Little is known about the sedimentology of the Cobham Formation as a result of contact metamorphism in the aureole of a posttectonic granite pluton southwest of the Cobham Range, but it is quartz rich at its base and carbonate rich near its top, suggesting inner continental-shelf sedimentation (Laird et al. 1971). The Goldie Formation is a ~2–4-km-thick siliciclastic succession composed predominantly of quartzofeldspathic sandstone and shale, with minor calcareous sandstone and matrix-supported conglomerates (Grindley 1963; Laird et al. 1971; Stump et al. 1988). The presence of tabular-bedded sandstone with cross-bedding, ripple lamination, and graded bedding led previous workers (e.g., Laird et al. 1971) to suggest that the Goldie represents deepwater turbidites. Our recent work indicates, instead, that most, if not all, Goldie rocks were deposited in a shallow marine setting (Myrow and Goodge 1999). Basaltic sills and pillow lavas (containing rare gabbroic bodies), as well as rhyolite and metarhyolite, are reported at several localities (Oliver 1972; Stump et al. 1988; Stump 1995).

Until now, there have been no paleontological finds from the Beardmore Group, so constraints on the presumed Proterozoic depositional age rested on regional stratigraphic arguments and isotopic data. Borg et al. (1990) suggested that the group be divided into an "eastern" type characterized by whole rock Nd-model ages of 1.61–1.68 Ga and a "Cotton Plateau" type defined as sandstone interlayered with pillow basalt (fig. 1). Basalts at Cotton Plateau are described as conformable within Goldie sandstone and as containing discontinuous, small bodies of gabbro (Stump et al. 1988). A Neoproterozoic age of Goldie deposition is based on a three-point, whole rock and mineral Sm-Nd isochron of 762 ± 24 Ma (Borg et al. 1990). This age was obtained from basalt and gabbro assumed to be coeval.

Detrital Zircon Age Results

We analyzed detrital zircons from four samples of fine-grained Beardmore Group sandstone (fig. 1). All but one sample (Cobham Formation sample 98–229) are from rocks mapped as the Goldie Formation. Detrital-zircon sample preparation and analytical procedures for measurement of U and Pb isotopes followed standard procedures, which we briefly summarize here. Representative zircon populations were handpicked, mounted in an epoxy disk, and polished to half section. All grains were imaged with cathodoluminescence (CL) before analysis. Isotopic measurements were conducted on both SHRIMP I and II ion microprobes at the Research School of Earth Sciences, Australian National University, according to methods described by Williams and Claesson (1987) and Pell et al. (1997). Most data were corrected for common lead with ^{204}Pb. Reference zircon AS-57 (1099 Ma) was analyzed after every six to seven unknown grains. Ages were calculated with either ^{206}Pb/^{238}U or ^{207}Pb/^{206}Pb, depending on the age of the grain. Generally, Archean, Paleoproterozoic, and Mesoproterozoic (≥1500 Ma) grain ages were determined with ^{207}Pb/^{206}Pb. Ages of concordant younger grains were calculated from ^{206}Pb/^{238}U; ages of discordant grains or those with high common Pb were calculated with ^{207}Pb/^{206}Pb. Errors for individual analyses are quoted at the 1σ level.

Approximately 70 grains were analyzed from each sample. The grains were selected to be as representative as possible of the range of morphologies, colors, and growth structures in the zircon population. Analysis of zircons containing a single dominant crystal domain as viewed by cathodoluminescence was generally straightforward. Many grains were composite, however, reflecting sequential igneous or metamorphic growth in the rocks of the sediment source. In those cases, the youngest dominant generation of zircon growth was dated. Although this method biases our data toward young ages, it minimizes the dating of inherited zircon cores, ensures that we are dating the principal igneous and metamorphic components in the source terrain, and provides the best constraint on depositional age. Analyses of all detrital grains are portrayed on modified logarithmic Tera-Wasserburg plots (fig. 2), which best illustrate the wide range of grain ages encountered in a sediment. Complete analytical data for all grains, including isotopic measurements and grain characteristics, are provided in tables 1–4 (which, along with table 5, are available from the *Journal of Geology*'s Data Depository upon request). Relative probabilities of grain ages from all samples are compared in figure 3.

Inboard Assemblage. Sample 98-229 is from the Cobham Formation in the southern Cobham Range, and sample 98-260 is a Goldie Formation sandstone from the northwest part of Cotton Plateau, about 3-km southeast of Panorama Point (fig. 1). Sample 229 is strongly recrystallized as a result of contact metamorphism, so its primary texture is not apparent. Sample 260 is a fine-to-medium sandstone that shows moderate-to-poor sorting and subangular-to-round grain shape. Quartz with minor muscovite and opaque grains is the dominant framework mineral. No feldspar was observed, but scattered granular calcite in sample 260 suggests that the original sediment contained some feldspathic material that has since been replaced. Most quartz grains in sample 260 are monocrystalline with minor undulose extinction, but some are poly-

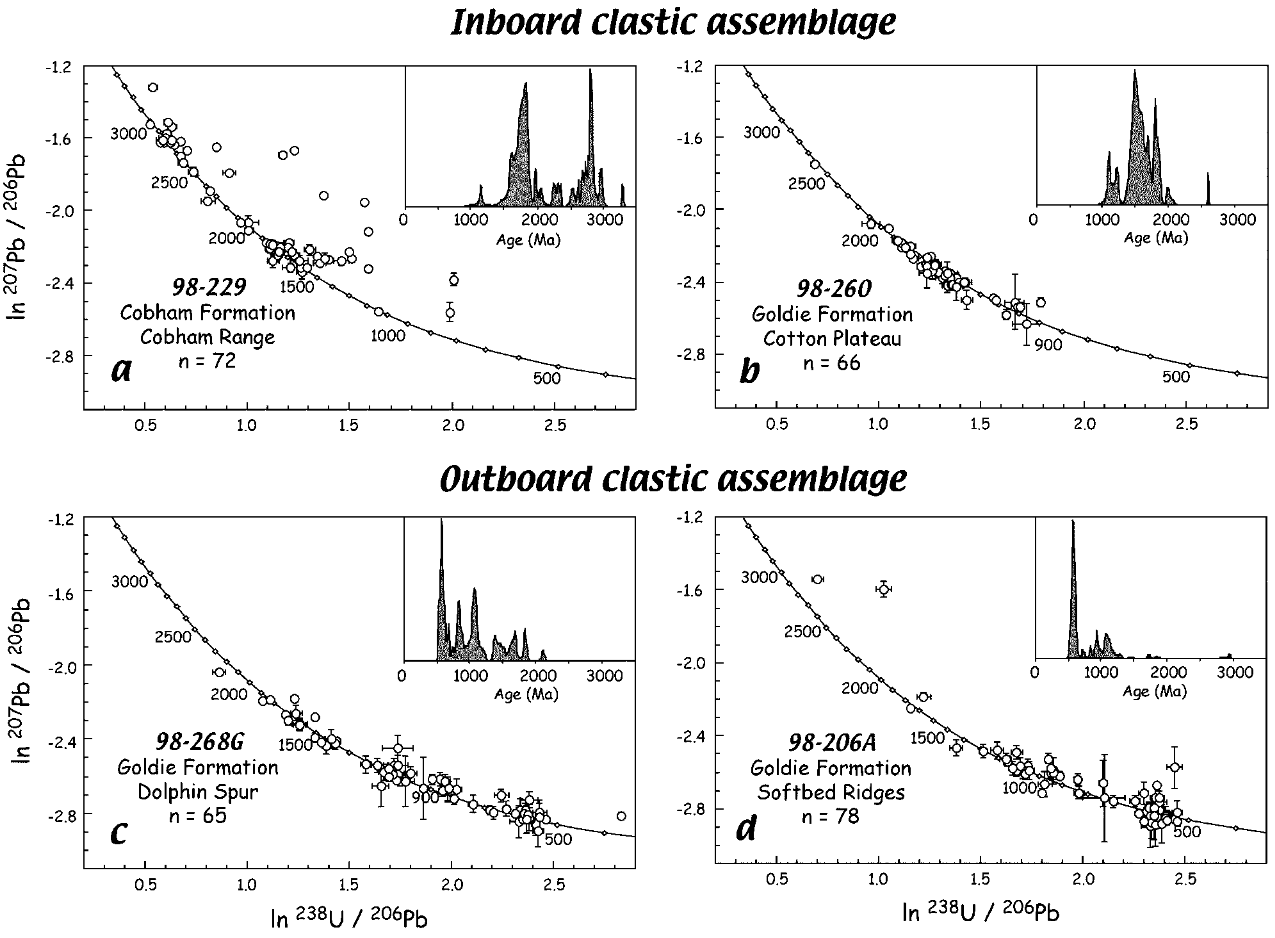


Figure 2. Logarithmic Tera-Wasserburg diagrams showing U-Pb analyses of detrital zircon grains in sandstone samples from the Cobham and Goldie formations (n = number of individual grains analyzed; ages are Ma). Insets show simplified age probability distribution. Errors for individual analyses are 1σ.

crystalline and of plutonic origin. Zircons from both samples are generally equant to elliptical in shape, with abundant broken and pitted surfaces that are indicative of abrasion by sedimentary transport and/or reworking. Prismatic, well-formed grains are rare.

The distribution of detrital ages (fig. 3*a*, 3*b*) shows a wide range of Archean and Proterozoic source components, which are dominated by composite groups at ~2810, ~1825, and ~1490 Ma. Subsidiary groups show that the input in sample 229 is somewhat bimodal, with major components of late Archean and Mesoproterozoic age, whereas sample 260 is dominated by a range of Paleoproterozoic-to-Mesoproterozoic components between 1.9 and 1.4 Ga. Both distributions reflect heterogeneous sources. Sample 260 contains a subpopulation of seven grains that yield highly concordant $^{207}Pb/^{206}Pb$ ages between 1.45 and 1.39 Ga, although this is difficult to resolve beneath the peak at 1490 Ma. Both samples show minor input from Grenville-age sources (1.2–1.0 Ga), and two discrete subpopulations are recognizable in sample 260. The youngest reliable grain ages in samples 229 and 260 are 1143 ± 15 Ma and 1065 ± 65 Ma, respectively.

These zircon characteristics and age patterns indicate that Cobham Formation sandstone has a late Neoproterozoic depositional age. Because the data for grain 13.1 in sample 229 are discordant, they are not useful in placing an older limit on the age of deposition. We think that the age from grain 67.1 gives a better constraint (deposition younger than ~1145 Ma). The Cobham sandstone represents a moderately mature, multicycle sediment that was probably derived from highly mixed sources dominated by 2.8- and 1.8–1.6-Ga crust. Tectonic fabrics in the Cobham Formation indicate that it is pre-orogenic with respect to Ross tectonism.

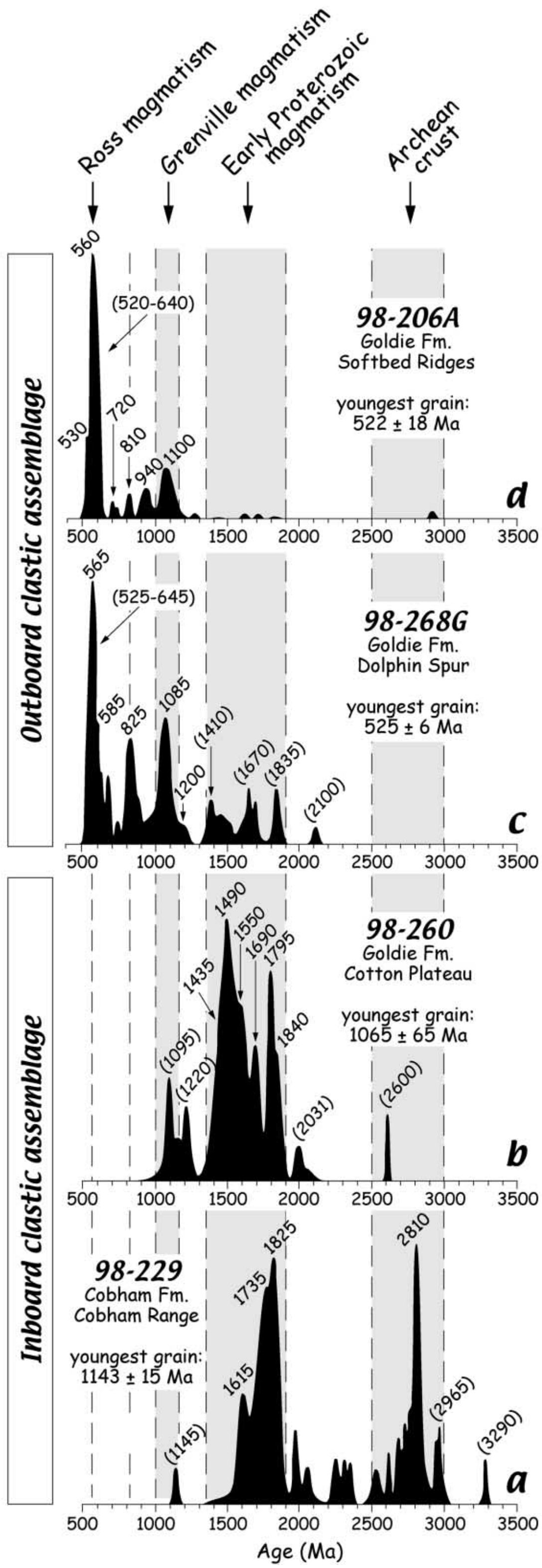


Figure 3. Relative probability histograms of detrital zircon U-Pb ages from Beardmore Group samples. As in figure 1, samples are grouped by assemblage. Histograms were constructed according to Dodson et al. (1988). The ages assigned to the peaks were derived from multicomponent mixture modeling (Sambridge and Compston 1994); the ages in parentheses were calculated as the simple means of discrete peaks. Samples from the inboard assemblage (*a*, *b*) are characterized by a greater proportion of Archean and Proterozoic age components, whereas samples from the outboard assemblage (*c*, *d*) are dominated by input from latest Neoproterozoic and Early Cambrian sources. The youngest grains in the outboard assemblage (~520 Ma) are indicated as minimum ages because of possible but undetermined Pb-loss; nonetheless, the presence of several grains with Early Cambrian $^{206}Pb/^{238}U$ ages is consistent with a late Early Cambrian or younger depositional age.

Goldie Formation sandstone from Cotton Plateau has a late Neoproterozoic maximum depositional age (≤1065 Ma) and was derived from a similarly mixed source area dominated by Paleoproterozoic igneous rocks. Deposition as late as ~665 Ma is suggested by a new zircon age for gabbro associated with the inboard assemblage (discussed in "Age of Cotton Plateau Gabbro"). A late Neoproterozoic depositional age is not at odds with the absence of detrital zircons with ages between 1065 and 665 Ma, since sedimentary deposits in general only record the ages of available source rocks and since discrepancies between depositional and provenance ages are common in the rock record. For instance, the detrital zircon age signature in basal sandstone of the Lower Cambrian Shackleton Limestone is similar to that of the sample of Goldie Formation from Cotton Plateau and also contains no grains younger than ~975 Ma (J. Goodge and I. Williams, unpubl. data). Sample 260 is texturally mature, and we infer a cratonic source of detritus in an area that was dominated by 1.9–1.4-Ga igneous rocks but that also included minor Grenville-age basement. In fact, we recognize at least two populations of ~1220- and ~1095-Ma zircons that are similar in age to two separate Grenville-age mobile belts in East Antarctica (Fitzsimons 2000). The presence of ~1.4-Ga zircons is particularly intriguing because there is no known basement of this age in East Antarctica or Australia. However, plutonic rocks of this age are characteristic of present-day North American basement, which suggests a former connection between Laurentia and East Antarctica, as discussed in "Implications for Rodinia."

Outboard Assemblage. Sample 98-268G is a Goldie Formation sandstone from the crest of Dolphin Spur, about 12 km east of Mt. Patrick and Beardmore Glacier, and sample 98-206A is a Goldie sandstone from Softbed Ridges near Lowery Glacier (fig. 1). Framework grains in both samples are equant-to-tabular, angular-to-subrounded, and show moderate sorting. Detrital grains consist mostly of quartz, with lesser amounts of plagioclase, microcline, muscovite, apatite, and rutile. Quartz grains are dominantly unstrained and monocrystalline, but some are polycrystalline and of igneous or metamorphic origin. Plagioclase (~15%) shows minor alteration to calcite. Detrital muscovite flakes are flat or bent around framework grains. Zircons are almost entirely bright, clear grains that show little evidence of transport and abrasion. Most are terminated, prismatic crystals, which suggests an igneous origin, and others are partly rounded, cloudy, pale-pink-to-purple grains of possible metamorphic origin.

In marked contrast to the inboard samples, the distributions of detrital ages in samples of the outboard assemblage (fig. 3*c*, 3*d*) are dominated by input from late Neoproterozoic and Early Cambrian sources, and the depositional ages are therefore younger than the youngest Early Cambrian grains. The histograms show subdued Archean and Proterozoic components, but the dominant ages are 1200–1000 (Grenville age), 825–810, ~720, and ~560 (Ross age) Ma. Sample 206A, in particular, has a nearly unimodal age distribution that indicates a dominant provenance of ~560 Ma. Zircons from the younger age groups have Th/U ratios (>0.3) and zoned internal structures characteristic of an igneous origin. Grains with low Th/U ratios (0.05–0.16) and uniform CL structure, traits suggestive of a metamorphic origin, are mostly 610–550 Ma. Sample 268G also contains several grains with concordant ages of 1465–1375 Ma, and sample 206A contains one grain with an age of 1451 ± 43 Ma. The youngest individual grains are ~525–520 Ma, which indicates that the outboard assemblage has an Early Cambrian or younger depositional age. Several other grains yielded ages ≤540 Ma, which confirms the presence of earliest Cambrian sources. A Cambrian age for the outboard assemblage is supported by the discovery of Cambrian-scale trace fossils at Softbed Ridges and Dolphin Spur (fig. 1). These consist of simple bedding-parallel feeding burrows with diameters in excess of 1 cm. This is considerably larger than the diameter of known Precambrian burrows. The textural immaturity of these samples, which is shown by moderate sorting, grain angularity, and prismatic-to-euhedral zircon shape, suggests that they represent first-cycle sediment.

The principal differences between these samples and those of the inboard assemblage are the less prominent contribution of Archean and Proterozoic material and the abundance of 580–520-Ma zircons. These rocks are dominated by fresh, young, locally derived material of igneous origin that was chiefly eroded from an early Ross-age source. Abundant 580–540-Ma zircons are older than the U-Pb ages commonly reported for plutons of the Granite Harbour batholith (generally 550–490 Ma; Gunner and Mattinson 1975; Encarnación and Grunow 1996; Read and Cooper 1999). We suggest, therefore, that this ~560-Ma component may be eroded from an early volcanic phase of the magmatic system. At the time of deposition, very little Archean and Proterozoic material was available to the basin. However, zircons of apparent metamorphic origin with ages between about 610 and 550 Ma indicate that the source terrain also included some late Neoproterozoic metamorphic basement. The outboard samples also contain significant contributions from Grenville-age basement and an ~825-Ma igneous center; the latter indicates input from an igneous source coeval with the 827 ± 6-Ma Gairdner dike system in southern Australia (Wingate et al. 1998).

Age of Cotton Plateau Gabbro

In the Cotton Plateau area, Goldie Formation siliciclastic rocks are associated with mafic metavolcanic units (see Stump 1995), including greenschist-facies pillow basalts and minor bodies of coarse-grained gabbro and/or plagiogranite. These units are variably sheared, which makes it difficult to determine primary geologic relationships with certainty. However, the pillow structures indicate submarine eruption, probably at the time of Goldie sedimentation, and the gabbros appear to be intrusive as coarser pods and apophyses within the basalts. To our knowledge, gabbro of this association is restricted to the general area of Cotton Plateau and is not found anywhere to crosscut sandstones as isolated bodies, dikes, or sills. We analyzed zircon from a sample (98-249B) of the gabbroic phase that we collected just north of the high point at the Palisades. This sample is a coarse-grained (2–4 mm) gabbro that contains subequal plagioclase and clinopyroxene and minor amphibole, quartz, and Fe-Ti-oxide. It has a hypidiomorphic-granular texture with subophitic appearance, but the plagioclase is moderately deformed, and the pyroxene is mostly replaced by chlorite + calcite.

Isotopic measurements were conducted in the Radiogenic Isotope Laboratory at the Massachusetts Institute of Technology. We followed the standard analytical procedures for zircon U-Pb analysis by ID/TIMS described by Bowring et al. (1998). The results of eight individual zircon grain analyses are shown on a concordia diagram (figure 4); complete analytical data are given in table 5.

Zircons from sample 98-249B are clear, doubly terminated crystals, many of which have abundant opaque inclusions. The zircons range from equant (150 μm) to elongate (400 × 65 μm) shape. Eight grains covering the range of morphologies were chosen for analysis. The data cluster near concordia but define a linear array with an upper intercept of 668.1 ± 1.2 Ma (MSWD = 0.13). The weighted mean $^{207}Pb/^{206}Pb$ date of all the analyses is 667.8 ± 0.6 Ma (MSWD = 0.28), which is indistinguishable from the upper-intercept date and is probably the best estimate of the age of the gabbro.

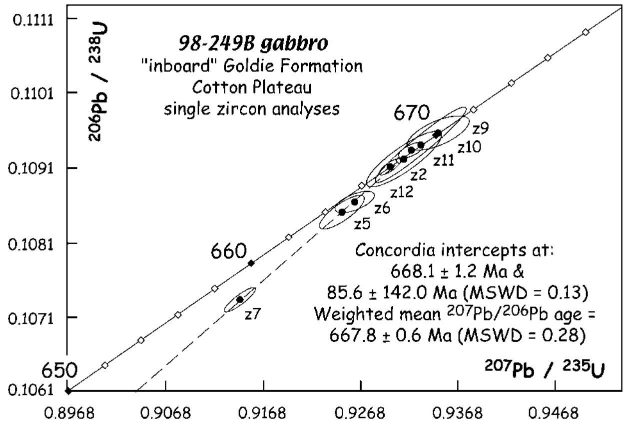


Figure 4. Concordia diagram showing U-Pb analyses of individual zircons from Beardmore Group gabbro at Cotton Plateau.

Discussion

Beardmore Group Revisions. According to new age data, rocks mapped as the Beardmore Group consist of at least two distinct successions of different depositional age and provenance: an older (≤670 Ma), mature inboard assemblage with a variety of Archean and Proterozoic age components (Cobham and inboard Goldie formations) and a much more volumetrically significant, younger (≤520 Ma) outboard assemblage that is dominated by Ross-age (580–520 Ma) igneous components (outboard Goldie). In general, the inboard assemblage contains a mixture of older, multicycle components, but the outboard assemblage reflects greater input from first-cycle igneous material. As mapped, the group is clearly not a uniform succession of Neoproterozoic siliciclastic deposits. Division of the Beardmore Group as suggested here is similar to revisions adopted for the Patuxent Formation of the Pensacola Mountains (Millar and Storey 1995; Rowell et al. 2001).

From the age and geographical distribution of these distinct assemblages (fig. 1), it might be inferred that the younger, outboard deposits rest depositionally on the inboard units. However, we know of no place where such a depositional relation can be unambiguously identified in the field because the sedimentary characteristics of the two assemblages are similar. In the eastern Holyoake Range, however, a gradational transition exists between Lower Cambrian Shackleton Limestone and overlying clastic strata of the upper Byrd Group, primarily the Starshot Formation (Myrow et al. 2002). We consider the outboard Goldie Formation to be equivalent to the Starshot Formation (fig. 5).

Therefore, the extent of the two assemblages as shown in figure 1 is interpreted on the basis of field relations combined with the distribution of sandstones containing Ross-age detritus.

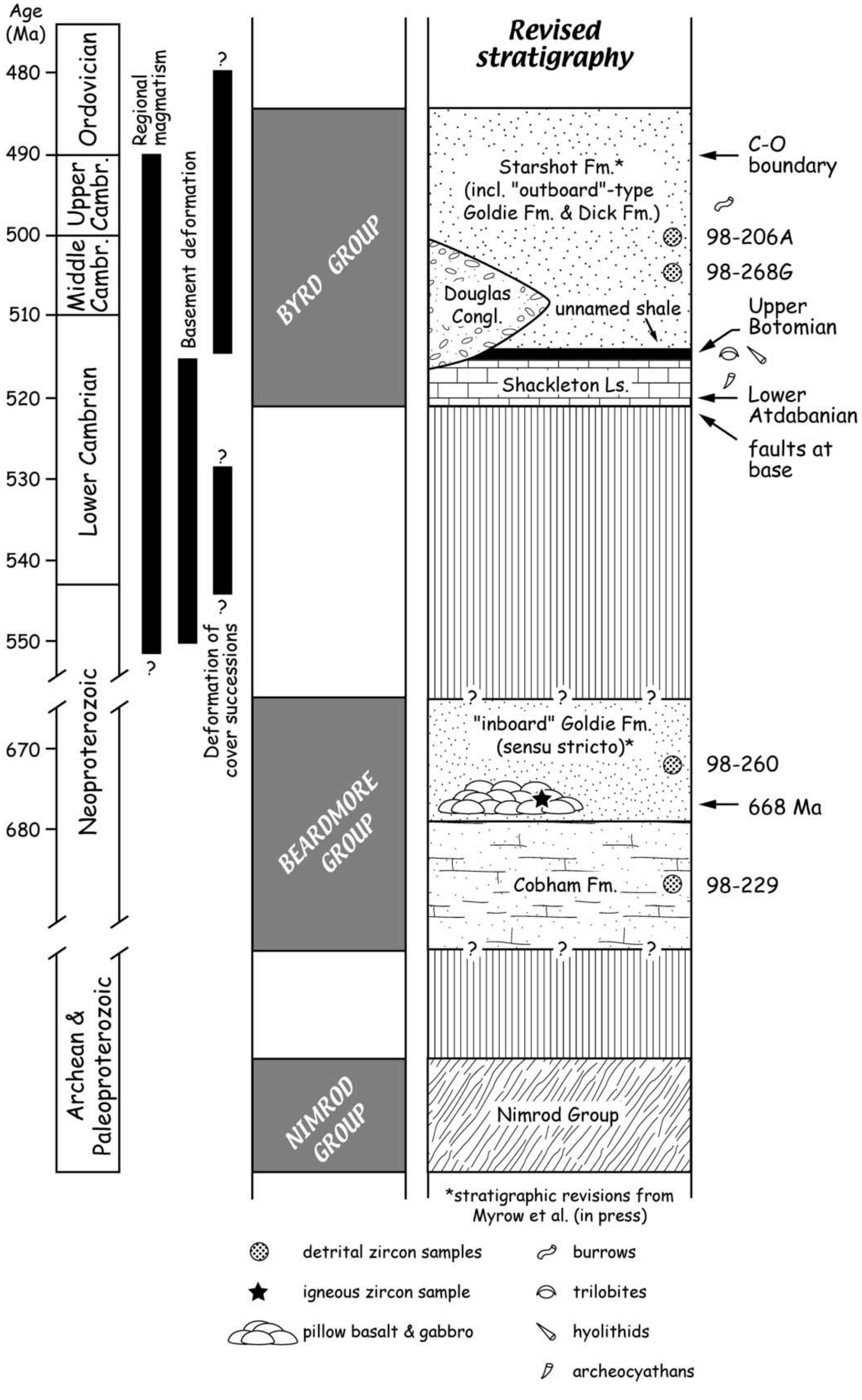
The youngest detrital zircons in the inboard sandstones are ~1065 Ma, yet a new zircon age from the Cotton Plateau gabbro of 668 Ma is probably closer to the depositional age of the inboard assemblage. Our gabbro U-Pb age is substantially younger than a widely quoted three-point Sm-Nd isochron age of 762 ± 24 Ma reported by Borg et al. (1990). It is, however, within the analytical uncertainty of their four-point isochron at 746 ± 82 Ma, which includes the whole rock gabbro value. Rocks at Cotton Plateau are strongly folded and interleaved by discrete shear zones (Stump et al. 1991), yet assuming that the pillow basalts and gabbro were eruptive at the time of sandstone deposition, the new age suggests that craton-margin sedimentation and magmatism were at least in part latest Proterozoic (~650 Ma or younger). An absence of Ross-age igneous material in the detrital zircon signatures, as seen in the outboard assemblage, indicates that these deposits are almost certainly older than ~580 Ma.

The late Early Cambrian depositional age for the outboard assemblage is substantially younger than the age previously inferred for the Beardmore Group. This discrepancy suggests that major stratigraphic revision is required (Myrow et al. 2002) and that we reconsider the depositional history along the paleo–Pacific East Antarctic margin. We interpret the outboard assemblage to be syntectonic because (1) its principal source was a proximal igneous terrain associated with the Ross Orogen, (2) Ross deformation in crystalline basement began as early as ~540 Ma, and (3) the main period of Ross tectonism is post–Early Cambrian (see Stump 1995; Goodge 2001). An Early Cambrian or younger age for the bulk of rocks mapped as the Goldie Formation requires remapping of these units as part of the Byrd Group. Stratigraphic revision has occurred with similar sandstone successions elsewhere in the Transantarctic Mountains (Millar and Storey 1995; Van Schmus et al. 1997; Vogel et al. 1999; Rowell et al. 2001), which suggests that widespread deposition of these thick siliciclastic deposits is related to orogenesis rather than to earlier rift-margin processes (see also Ireland et al. 1998).

The positions of these two sedimentary assemblages relative to the inferred cratonic margin (fig. 1) and their different provenance suggest a shift in time and space from inner, passive-margin sedimentation derived from the adjacent craton to an outer-margin or forearc succession receiving the bulk of its detritus from nearby igneous sources. The absence of 580–520-Ma volcanic rocks in this sector of the Ross Orogen may be a consequence of arc denudation. The accumulated sediment in turn hosted the emplacement of late-stage, post-tectonic plutons. The relation between magmatic/orogenic activity and sedimentation, involving the production and dispersal of large volumes of sediment, may be similar to Mesozoic denudation of the Sierra Nevada volcanic arc and deposition of the Great Valley sequence (Ingersoll 1983; Linn et al. 1992).

Mesoproterozoic Nd-model ages and ϵ_{Nd} values of −5 to −6 from the "eastern-type Goldie" (our outboard assemblage) led Borg et al. (1990) to define a so-called Beardmore microcontinent accreted terrane. Sedimentary units in this terrane were thought to have no sources from the East Antarctic craton. Others have invoked similar tectonic models of a "Queen Maud terrane" accreted during Ross-age plate convergence (e.g., Encarnación and Grunow 1996; Grunow and Encarnación 2000). Although the eastern-type Goldie yielded Nd-model ages of 1.68–1.61 Ga, our detrital zircon data show that this outboard Goldie contains a highly varied provenance signature, including not only Mesoproterozoic components but also much younger and more dominant components that better reflect the

Figure 5. Proposed stratigraphic revision of Neoproterozoic and lower Paleozoic sedimentary units in the central Transantarctic Mountains (after Myrow et al. 2002). Revision reflects data from detrital zircons in sandstone and igneous zircons from gabbro, all of which were originally mapped as belonging to the Beardmore Group. The ages of the units are also constrained by new fossil discoveries and observed stratigraphic relationships (see Myrow et al. 2002). In the revised scheme, our "inboard" Goldie should be considered Goldie Formation sensu stricto. It has a Neoproterozoic age and, along with the Cobham Formation, comprises the Beardmore Group. The inboard Goldie Formation includes rocks referred to as "Cotton Plateau–type Goldie" by Borg et al. (1990, p. 6662). The "outboard" Goldie is now included, together with the Dick Formation, within the Starshot Formation of the Byrd Group. Our outboard assemblage (fig. 1) is therefore equivalent to the Starshot Formation, as defined in this broad sense. It includes rocks referred to as "eastern-type Goldie" by Borg et al. (1990, p. 6662). Basement rocks in the region are represented by Archean and Paleoproterozoic gneisses of the Nimrod Group (Goodge et al. 1993, 2001; Goodge and Fanning 1999). The ages of igneous and tectonic activity in the region are shown by black bars to the left.



*stratigraphic revisions from Myrow et al. (in press) sedimentary source. Our data, combined with paleocurrents indicating a westerly source (Myrow et al. 2002), suggest instead that the outboard units were derived from a cratonic area overlain by a continental-margin volcanic arc. The Nd-isotope ages cannot, therefore, be used either to constrain a depositional age or as a measure allochthoneity. On the contrary, both the inboard and outboard successions can be tied to the presently adjacent East Antarctic craton based on the following lines of evidence: (1) the persistent cratonic age signature in all of the samples studied here, which is consistent with known East Antarctic basement provinces (Tingey 1991); (2) clastic units of the upper Byrd Group (outboard assemblage) rest depositionally upon platformal Shackleton Limestone in the Holyoake Range (Myrow et al. 2002); and (3) eastward paleocurrents in the outboard assemblage. All of these siliciclastic strata from the central Transantarctic Mountains should therefore be considered to be autochthonous rather than allochthonous with respect to East Antarctica.

Implications for Rodinia. East Antarctica is recognized as a keystone in most reconstructions of Rodinia (Hoffman 1991; Moores 1991; Dalziel 1997; and others). As such, the evolution of its paleo-Pacific margin may place important constraints on matching conjugate margins and the timing of rifting. Unique detrital zircon components in the Beardmore Group may help resolve questions concerning the fit of East Antarctica with other cratons comprising Rodinia. Three of our samples contain zircons with concordant ages between 1465 and 1375 Ma. Sample 260 contains seven grains (11%), sample 268G contains five grains (8%), and sample 206A contains one grain with ages in this range. Their growth textures and Th/U ratios indicate an igneous origin, and their morphology indicates they are mostly first-cycle sedimentary components. The concordant ages of these grains indicates they are not simply partly reset older zircons because the analytical precision of ^{207}Pb/^{206}Pb allows us to distinguish a concordant 1.4-Ga age from a discordant older age. In addition to the samples discussed here, four other Beardmore Group sandstones contain notable populations of ~1.4-Ga zircons (J. Goodge and I. Williams, unpub. data).

Detrital components of ~1.4-Ga age may reflect erosion of a Mesoproterozoic igneous province like the trans-Laurentian anorogenic granite belt (Anderson 1983; Windley 1993), which in the southwestern United States includes plutons with ages between 1.46 and 1.36 Ga (Hoffman 1989). To our knowledge, there are no cratonic sources for detritus of this age in present-day Antarctica or Australia. Paleogeographic models (e.g., Dalziel 1997) suggest that East Antarctica and Laurentia were separated by Cambrian time, precluding a direct input of these ~1.4-Ga components to the outboard assemblage deposits from Laurentia. Such first-cycle sediment, derived from western (continental interior of East Antarctica) sources, can be explained if the trans-Laurentian anorogenic igneous province extends into East Antarctica but is now ice covered. Age components of 1.8–1.6 Ga, similarly predicted by extension of Mojave-Yavapai-Mazatzal crust into East Antarctica, are also abundant in the detrital populations. Previous correlation of Laurentian and Antarctic cratonic basement provinces (Borg and DePaolo 1994) is supported by these unique Proterozoic detrital age components. We suggest that the 1.4-Ga signature, unlike the ubiquitous Grenville-age belts, may therefore provide a good geologic tie between East Antarctica and Laurentia in the Rodinian supercontinent. The proportions of the ~1.4-Ga age component in our samples is not unlike that found by Rainbird et al. (1992) in Neoproterozoic sandstone of the Shaler Group in the Canadian Arctic. The Shaler sandstone is interpreted as having a provenance essentially stretching across the entire Laurentian craton and as containing a 10% population of ~1.4-Ga zircons that can be inferred to come from the trans-Laurentian igneous province. Therefore, even a small fractional population, if discrete, may serve as a unique source characteristic.

Elsewhere within Gondwana there are some rocks of similar age. Granitic rocks associated with the Kibaran Orogeny exist in the Irumide belt of southern Africa, but most are 1.33–1.25 Ga (Cahen et al. 1984; Tack et al. 1994). A U-Pb age of 1393 ± 22 Ma from a plagiogranite dike within ophiolitic rocks of the Zambezi belt suggests there is some pre-Kibaran material (Oliver et al. 1998); however, this is from a small remnant of oceanic crust by comparison with the widespread Laurentian granite province and is an unlikely source for the Beardmore Group. Otherwise, 1.4 Ga is not well represented geologically in Africa (Cahen et al. 1984). It is therefore unlikely that central or southern Africa could yield much detritus of ~1.4-Ga age. Furthermore, although these African belts might plausibly have provided some detrital zircon of the right age to the outboard Goldie assemblage if transported off the developing East African Orogen, they are unlikely sources for the inboard assemblage because the Antarctic deposits probably predate Pan-African closure of the Mozambique Ocean (about 650–550 Ma).

In addition to their relevance for Rodinia correlations, our data also bear on the age of rifting along the proto-Pacific margin of East Antarctica. Previous suggestions for ~750-Ma rifting along the Antarctic margin were based on ages from two mafic igneous units in the Transantarctic Mountains. One, an 828–664-Ma Sm-Nd isochron age for gabbro at Cotton Plateau (Borg et al. 1990), is superceded by the precise zircon age of 668 Ma presented here. The second, a Nd-model age of 800–700 Ma for metabasalt in the Skelton Glacier area (Rowell et al. 1993), is imprecise. In addition to this age discrepancy, the restricted extent of inboard Goldie rocks and their metamorphic grade and structural complexity make a rift origin difficult to prove. Although conglomeratic facies exist in the inboard Goldie, the sandstone-rich strata that we studied were texturally mature and show evidence for deposition on a storm-dominated shelf. A heterogeneous zircon provenance and the absence of arkosic facies are consistent with passive-margin sedimentation rather than deposition in an active rift environment. Therefore, direct evidence of rift-related magmatism and sedimentation in Antarctica at ~750 Ma is suspect.

If one assumes that the mafic igneous rocks at Cotton Plateau are indeed representative of rifting, then the formation of a new Antarctic rift margin may be appreciably younger than 750 Ma, as is indicated by the new gabbro age. This is at odds, however, with paleomagnetic and stratigraphic evidence for rifting in Australia. Wingate and Giddings (2000), for example, use paleomagnetic data from the Mundine Well dike swarm in western Australia to suggest that northern Laurentia and Australia separated prior to 755 Ma. These paleomagnetic data are compatible with stratigraphic data from the Neoproterozoic margin of eastern Australia (Adelaide Geosyncline) that Preiss (2000) used to argue for discrete episodes of "rifting" characterized by crustal extension and basin formation between ~830 and 780 Ma. The basal Willouran succession in the Adelaidean contains the Wooltana Volcanics, which are considered to be the eruptive equivalent of the 827 ± 6-Ma Gairdner dikes (Wingate et al. 1998). This igneous activity is interpreted as the magmatic signal of continental rifting. Higher parts of the Willouran and Torrensian successions contain felsic volcanic units (Rook Tuff and Boucaut Volcanics) with ages of 802 ± 10 Ma and 777 ± 7 Ma, respectively (Fanning et al. 1986; C. M. Fanning, unpubl. data). Although these igneous units are cited as evidence of rifting (Powell et al. 1994), there is little geochemical basis for this claim. Preiss (2000) interpreted the upper Sturtian and lower Marinoan sections (about 680–650 Ma) as evidence of sag-phase deposition related to continental separation. Younger (586 ± 7 Ma) Mt. Arrowsmith Volcanics, which exhibit geochemical affinities to modern African rift lavas, are suggested to represent renewed "rifting" along the developing Australian margin (Crawford et al. 1997). Veevers et al. (1997), on the other hand, interpreted this igneous activity as a sign of rifting along the Australian margin in the latest Proterozoic (580–560 Ma). Thus, although there is some remaining uncertainty, the evidence from southeast Australia appears to indicate formation of early Neoproterozoic rift basins beginning about 830 Ma, followed by episodic extension, and development of a true passive margin by about 680–650 Ma. Evidence of latest Neoproterozoic volcanism and a shift to more juvenile sources of detritus by the Early Cambrian (Ireland et al. 1998; Turner et al. 1993) may reflect a fundamental change in the tectonic regime to that of an incipient convergent margin. In this context, "rifting" along the East Antarctic margin at ~750 Ma appears unlikely.

If mafic volcanism in the inboard Goldie Formation was not associated with rifting, then these rocks, which contain Nd-isotopic signatures indicating an oceanic mantle source (Borg et al. 1990), would likely represent a postrift eruptive phase associated with continued extension of the existing rifted margin. This interpretation better fits the sedimentological and provenance characteristics of the inboard Goldie. Such igneous activity would correspond in time with tectonically induced subsidence events recorded in postrift Sturtian-Marinoan intracratonic and marginal-basin successions in Australia (Lindsay et al. 1987; Preiss 2000). It also leads to more plausible plate displacement rates following Rodinia breakup. Between 670 and 600 Ma, East Antarctica could only have been displaced on the order of about 3500 km (assuming an average rate of 5 cm/yr) before subsequent closure of the Mozambique Ocean and suturing of the East Gondwana cratons (crust of present-day Africa, India, Madagascar, and East Antarctica) (Fitzsimons 2000; Boger et al. 2001). Paleogeographic reconstructions (e.g., Dalziel 1997) indicate that this would be an insufficient distance to account for the displacement of East Antarctica during the complete Rodinia-Gondwana transformation if 668 Ma represented the age of initial rifting. On the basis of these relationships, it therefore appears more likely that the mafic igneous rocks and their host sediments of the inboard Goldie are representative of postrift extension and sedimentation in the late Neoproterozoic (≤670 Ma). This is distinctly older, however, than 580–560-Ma extensional events in eastern Australia (Veevers et al. 1997) and the estimated onset of subsidence in western Laurentia between 600 and 550 Ma (Bond et al. 1984; Bond 1997). Differences in the ages of extension and subsidence related to Rodinia breakup may therefore indicate a diachronous separation of East Gondwana from Laurentia.

Whatever tectonic model may explain the nature and timing of events related to the Rodinia breakup, the timing of rifting along the Antarctic margin remains enigmatic by eliminating an oft-quoted age constraint. According to detrital zircon age characteristics, however, the sedimentary record from the Beardmore Group reflects late Neoproterozoic passive-margin deposition followed by a profound change to active-margin molasse deposition beginning in the Early Cambrian. The presence of ~1.4-Ga zircons in these autochthonous Antarctic deposits provides a possible Rodinian link between Antarctica and the present-day southwest Laurentian region.

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