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INSIDE

Refining Rodinia: Geologic Evidence for the Australia–Western U.S. connection in the Proterozoic

Karl E. Karlstrom, kek1@unm.edu, *Stephen S. Harlan**, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131
Michael L. Williams, Department of Geosciences, University of Massachusetts, Amherst, MA, 01003-5820, mlw@geo.umass.edu
James McLelland, Department of Geology, Colgate University, Hamilton, NY 13346, jmclelland@mail.colgate.edu
John W. Geissman, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, jgeiss@unm.edu
Karl-Inge Åhäll, Earth Sciences Centre, Göteborg University, Box 460, SE-405 30 Göteborg, Sweden, ahall@geo.gu.se

ABSTRACT

Prior to the Grenvillian continent-continent collision at about 1.0 Ga, the southern margin of Laurentia was a long-lived convergent margin that extended from Greenland to southern California. The truncation of these 1.8–1.0 Ga orogenic belts in southwestern and northeastern Laurentia suggests that they once extended farther. We propose that Australia contains the continuation of these belts to the southwest and that Baltica was the continuation to the northeast. The combined orogenic system was comparable in length to the modern American Cordilleran or Alpine-Himalayan systems. This plate reconstruction of the Proterozoic supercontinent Rodinia called AUSWUS (Australia–Southwest U.S.) differs from the well-known SWEAT (Southwest U.S.–East Antarctic) reconstruction in that Australia, rather than northern Canada, is adjacent to the southwestern United States. The AUSWUS reconstruction is supported by a distinctive "fingerprint" of geologic similarities and tectonic histories between Australia and the southwestern United States from 1.8 to 0.8 Ga, and by a better agreement between 1.45 and 1.0 Ga paleomagnetic poles for Australia and Laurentia.

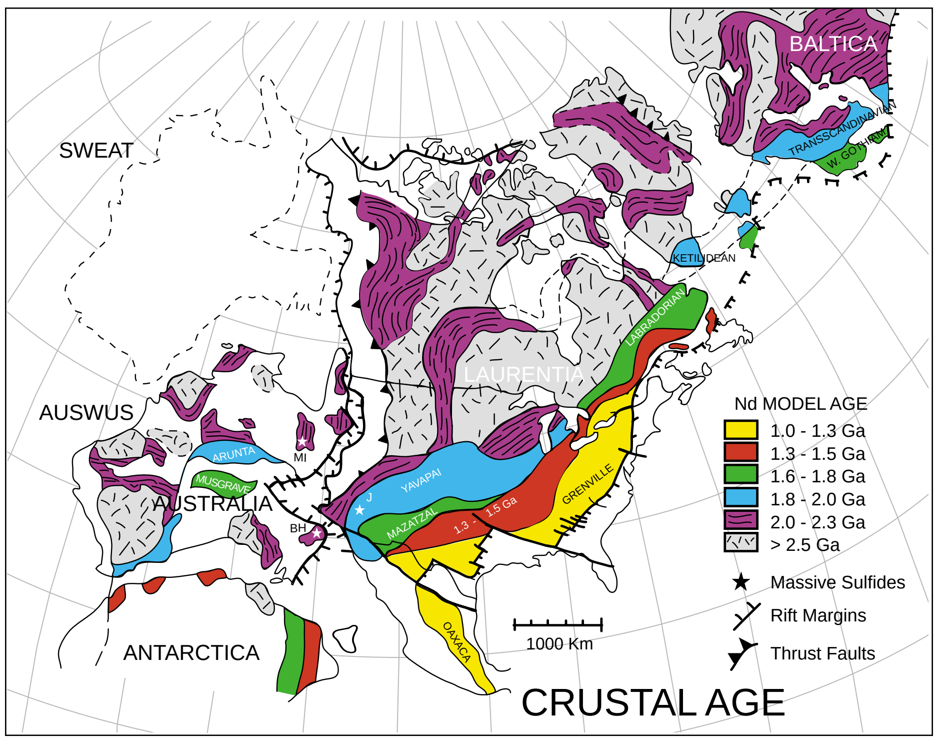

Figure 1. AUSWUS reconstruction for 1.7 to 0.8 Ga, modified from Brookfield (1993). The Tasman line forms the eastern edge of Proterozoic Australia (Myers et al., 1996); the $^{87}Sr/^{86}Sr$ = 0.706 line marks the west edge of Proterozoic Laurentia. Continents were rotated to this configuration about an Euler pole located at 51.46°N 106.70°E, rotation angle 114.33°. Both continents appear in equal-area projection in North American coordinates. The position of Australia in the SWEAT reconstruction is shown for comparison (from Moores, 1991). Crustal age provinces inferred from Nd data. Massive sulfide deposits of Broken Hill (BH) are to similar deposits in Jerome (J) in central Arizona and Mount Isa (MI) is across from the Carlin area of Nevada.

INTRODUCTION

Many recent papers have concluded that a supercontinent called Rodinia existed in the Neoproterozoic between 1.0 and 0.8 Ga. There is speculation that the breakup of Rodinia may have been related to dramatic changes in Earth systems such as diversification of life, multiple low-latitude glaciations, fluctuating ocean chemistry, and long-lived mantle convection patterns (Dalziel, 1997; Hoffman et al., 1998; Evans, 1998). However, the duration and configuration, and even the existence (Piper and Zhang, 1999), of this late Proterozoic supercontinent remain uncertain. Detailed reconstructions are hindered by absence of a sea-floor record, lack of sufficient geochronologic information to show synchroneity of supercontinent assembly and breakup, lack of high-quality apparent polar wander paths (APW) for Precambrian rocks of many continents, and later modifications to Precambrian plate margins during the Phanerozoic. Thus, the implications of possible pre-Pangean supercontinents for the evolution of Earth systems in general are difficult to evaluate.

One approach to supercontinent reconstructions is to try to match rifted margins of a given age. Reconstructions of the Mesozoic supercontinent of Pangea account for the shape and length of rift

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*Present address: P.O. Box 25046, MS 980, Federal Center, Denver, CO 80225, sharlan@crgdmail1.cr.usgs

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margins and also satisfy sea-floor magnetic data from Mesozoic–Cenozoic ocean basins. Earlier Rodinia reconstructions (Dalziel, 1997) have tried to match late Precambrian rift margins that developed during the breakup of Rodinia. Laurentia was nearly circumscribed by late Precambrian rift margins and thus could have had a central position within Rodinia. Sedimentary subsidence curves suggest that rifting took place in the latest Precambrian on many continental margins (Bond et al., 1984). However, uncertainties regarding timing of rifting, evidence for multiple rift events, and the probable presence of continental fragments (e.g., South China; Li et al., 1995) complicate the "rift-budget" approach for Proterozoic supercontinents.

Another reconstruction tool is the use of piercing points (unique points that were adjacent before rifting) between continents. For Pangea, it has been possible to match orogenic belts, fossil assemblages, and glaciogenic sequences. For Rodinia, the most widely used piercing points are segments of the 1.0 Ga (Grenville-age) orogenic belts that record continent-continent collisions during assembly of Rodinia. However, the "Grenville-age" belts themselves remain poorly understood. Most have older (Paleoproterozoic and Mesoproterozoic) and/or younger (Pan-African) histories, such that the proposed continuity of these orogens during assembly of Rodinia and their use as piercing points (Unrug, 1997) may be substantially oversimplified.

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The approach in this paper is to compare the tectonic evolution of key cratons within Rodinia. For Australia and Laurentia, we evaluate the SWEAT reconstruction of Rodinia and propose an alternate reconstruction, AUSWUS (Fig. 1). For Laurentia and Baltica, we support the reconstruction of Park (1995) and Åhäll and Gower (1997). This approach is not global in scope, but it has global implications. Our proposed long-lived juxtaposition of Australia, Laurentia, and Baltica provides a set of testable implications for the tectonic evolution of these cratons and an alternate hypothesis for Proterozoic supercontinent reconstructions.

Studies of Proterozoic rocks of the southwestern United States over the past few decades have led to a clearer understanding of its tectonic history. This history involves: (1) derivation of the crust from mantle sources from 1.8 to 1.6 Ga; (2) magmatic and metamorphic events from 1.5 to 1.3 Ga; (3) continent-continent collision and failed intracratonic rifting from 1.3 to 1.0; and (4) rifting and margin subsidence from 0.8 to 0.55 Ga, forming the early Paleozoic rift margins of Laurentia. The southeastern edge of Laurentia grew southward from 1.8 to 1.0 Ga, evolving as a long-lived, but episodic, convergent margin that produced a set of northeast-striking orogenic belts. The 800-m.y. orogenic history of these belts can be used as a "fingerprint" to identify the cratons that were adjacent during the Proterozoic.

SWEAT MODEL

The most influential continental reconstruction for the late Precambrian has been the SWEAT hypothesis (Moores, 1991; Hoffman, 1991; and Dalziel, 1991). In this model, the western U.S. is matched to Antarctica, western Canada to Australia, and the truncated 1.0 Ga Grenville orogen in Texas to East Antarctica.

Recent geologic data and a reassessment of the paleomagnetic database raise doubts about the main piercing points used for the SWEAT reconstruction. Moores (1991) and Dalziel (1991) suggested that the truncated Grenville front of west Texas could be matched to the Weddell Sea area of Antarctica. However, Gose et al. (1997) suggested that this part of Antarctica was within west Gondwana (Kalahari) at 1.1 Ga, not east Gondwana, negating this piercing point (Dalziel, 1997, p. 33). All other proposed piercing points are also in question. For example, lithologic and isotopic similarities between the Shackleton Range of Antarctica and the Yavapai province of Arizona are weakened by isotopic data that show Archean crustal components in the Shackleton Range (Helper et al., 1996).

Proposed connections between Australia and northern Canada also are in doubt. The striking lithostratigraphic similarity between Neoproterozoic sequences of the Adelaidian rocks of Australia and the Mackenzie-Windermere sections of Canada (Young, 1992) do not provide piercing points for reconstructions, because these sequences can also be correlated southward along the Cordilleran margin (Link et al., 1993), and perhaps globally (Hoffman et al., 1998). Similarly, the ca. 780 Ma mafic dikes of northwest Canada, Montana, and Wyoming, postulated to be part of a plume-generated radiating swarm (Park et al., 1995), are younger than the 827 Ma Australian Gairdner mafic dikes and are probably not part of a single event (Wingate et al., 1999).

AUSWUS MODEL: AN ALTERNATIVE RECONSTRUCTION

Proposed modifications of the SWEAT reconstruction have placed Australia farther south relative to North America. Ross et al. (1992) suggested that 1580– 1600 Ma detrital zircons in the Belt Supergroup were derived from the Gawler Range volcanic rocks of South Australia and indicate that Australia was well south of the original SWEAT position (Fig. 1). Similarly, Borg and DePaolo (1994) speculated that the Ross et al. (1992) reconstruction might explain Nd isotopic provinces in Antarctica, if terranes had been translated southward as allochthonous strike-slip blocks. However, neither these provenance nor Nd province studies provide unique piercing points.

Brookfield (1993) placed Australia adjacent to the western United States by matching inferred rift-transform segments of Proterozoic rift margins. Using a modified version of the Brookfield (1993) reconstruction (Fig. 1), we propose that Australia was adjacent to the southwestern U.S. during much of the Proterozoic. To test this hypothesis, we have rotated proto-Australia into North American coordinates using an Euler pole at 51.46°N, 106.70°E (angle of rotation of 114°). We evaluate this reconstruction here for four Proterozoic time periods.

Crust Formation and Paleoproterozoic Assembly

The core of Laurentia consists of a mosaic of Archean cratons stitched by 1.9–1.8 Ga orogenic belts (Fig. 1). This is similar to western and northern Australia (Myers et al., 1996) and Baltica (Gorbatschev and Bogdanova, 1993). Nd model ages, often interpreted as the time of derivation of the crust from the mantle, are 2.0–2.3 Ga in northeastern Australia (Ross et al., 1992; Blewett et al., 1998), northwestern Canada, and the Mojave province (Bennett and DePaolo, 1987) and do not readily distinguish between the SWEAT and AUSWUS models. However, south of its Archean core, Laurentia is characterized by juvenile Proterozoic orogens, derived from the mantle at 2.0–1.8 Ga (Yavapai province) and 1.8–1.6 Ga (Mazatzal province; Karlstrom and Bowring, 1993). These belts have potential counterparts (based on Nd model ages) in the Arunta and Musgrave blocks (Zhao and McCulloch, 1995) and the Transscandinavian igneous belt and Gothian terranes of Baltica (Gorbatschev and Bogdanova, 1993). The sequence of orogens gets progressively younger southward and, collectively, could provide a set of piercing points.

Paleoproterozoic rocks in the southwestern U.S. and Australia are similar in composition and tectonic setting. Juvenile arc assemblages are present in both areas (Yavapai in Laurentia and Arunta in Australia), as are quartz arenite–rhyolite cover sequences (Mazatzal in Laurentia and Reynolds-Musgrave in Australia; Dirks and Wilson, 1990). Also, major ore-deposit districts broadly match up (Fig. 1). Proterozoic rocks in both regions record progressive heterogeneous, middle-crustal shortening from 1.8 to 1.6 Ga, compatible with progressive thickening and stabilization of juvenile arc terranes to form new continental lithosphere (Karlstrom and Williams, 1998; Collins and Shaw, 1995). The 1780–1730 Ma Strangeways orogeny in the Arunta Inlier could be broadly correlative with the 1780–1690 Ma accretion of juvenile arcs in the southwestern United States. Likewise, the 1680–1660 Arglke event in the Arunta Inlier could be correlative with the 1650 Ma Mazatzal orogeny.

Intracratonic A-type Magmatism and Related Tectonism

A prominent feature of the Paleoproterozoic orogens in Laurentia-Baltica is a suite of bimodal plutonic and volcanic

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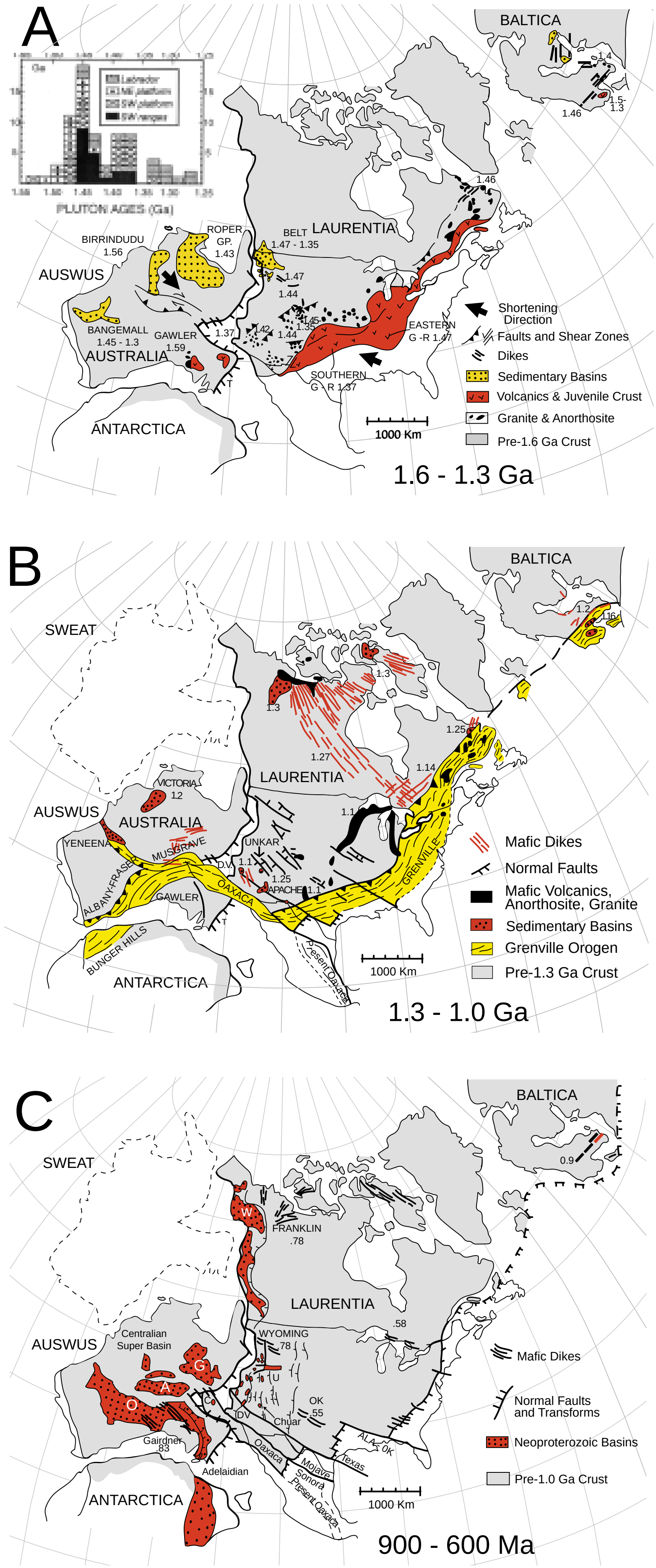

Figure 2. AUSWUS reconstruction for three time slices using the reconstruction of Figure 1. A: Orogenic belts and A-type granites and anorthosites, 1.6–1.3 Ga; G-R = granite rhyolite provinces; histogram shows wide variation in ages of A-type magmatism along the orogen in Laurentia (Hoffman, 1989). B: Grenville orogenic belts (yellow) are shown with foliation trends; temporally-coincident northeast intracratonic extension is recorded by mafic dikes (red) and normal faults. Oaxaca is restored along the Mojave-Sonora megashear. C: Extension and sedimentation prior to and synchronous with supercontinent fragmentation, 900–600 Ma. The Centralian superbasin includes the Officer basin (O), Amadeus basin (A), Georgina basin (G), and Adelaidian basin.

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rocks that were emplaced episodically from 1.6 to 1.2 Ga (Fig. 2A). Although their origin is enigmatic, they form distinctive intracratonic units that allow correlation across the Atlantic Ocean—e.g., at 1.46 Ga (Åhäll and Connelly, 1998). Although traditionally termed A-type for “anorogenic,” there is increasing evidence for an orogenic linkage of Mesoproterozoic rocks in eastern Laurentia (Rivers, 1997), Baltica, and the southwestern United States (Nyman et al., 1994). These intracratonic events could have echoed subduction-related and transcurrent tectonism near the plate margin, but much of the plate margin record has been obscured by Grenville tectonism and mid-continent Paleozoic cover sequences.

In Australia, A-type granites of the Gawler craton are older (1.6 Ga) than, but similar in composition and character to, those of southwestern Laurentia, and they could be a continuation of an A-type granite belt. This observation seems incompatible with interpretations that the Gawler craton was “assembled” with northern Australia across the Albany Fraser belt at 1.1 Ga (Myers et al., 1996), but other models suggest Paleoproterozoic connections between Gawler and northern Australia (Teasdale, 1997) and invoke progressive, largely intracratonic deformation from 1.5 to 1.0 Ga in the Albany-Fraser belt.

Sedimentary basins of 1.5–1.3 Ga are also present in each continent. The Belt basin of western Laurentia accumulated tens of kilometers of sediment between 1.47 and 1.35 Ga (Aleinikoff et al., 1997). The Roper Group, Birrindudu Basin, and Bangemall Basin of similar age form a zone parallel to the inferred transpressive orogen in Australia (Myers et al., 1996) and could be a sedimentary response to the 1.4 Ga orogenic event. Inferred shortening directions in Laurentia (west-northwest; Nyman et al., 1994) and Australia (southeast; Myers et al., 1996) are similar in the AUSWUS reconstruction, consistent with intracratonic dextral transpressive deformation in both continents

Grenville Tectonism

Tectonism that took place between 1.3 and 1.0 Ga from Labrador to Mexico (Fig. 2B) is broadly referred to as the Grenville orogeny (e.g., Davidson, 1995). This orogeny culminated (and ended) a nearly 1-b.y. history of tectonism along a convergent margin in southern Laurentia. It included early magmatism, metamorphism, and arc accretion to Laurentia (~1.3–1.17 Ga), intraplate magmatism (Eastern Grenville province; 1.16–1.13 Ga), and finally collisions with masses outboard to the southeast (possibly Amazonia and Kalahari). Grenvillian plutonism and metamorphism are generally imprinted on older (~1.7–1.45 Ga) crust corresponding to the Yavapai and Mazatzal provinces of the southwestern United States (Davidson, 1995). Juvenile Grenvillian crust was added as well (e.g., Rivers, 1997).

Within Australia, orogenic events in the Albany-Fraser and Musgrave belts (Fig. 2B) correspond in style and age to the ~1.3–1.0 Grenville orogeny of Laurentia (Clarke et al., 1995). These belts are almost exclusively underlain by older crust (Ross et al., 1992), generally in the range 1.9–1.6 Ga (Yavapai, Mazatzal). Both the Albany-Fraser and Musgrave belts show evidence of ~1.3 Ga plutonism consistent with arc-related settings, orogeny, and regional high-grade metamorphism between ~1.3 and 1.2 Ga. This, in turn, was followed (1.18–1.14 Ga) by "enriched" (intraplate) granitic magmatism that extends northward into the Arunta block, where alkaline intrusions also occur. Post–1.15 Ga events are well developed only in the Musgrave belt where mafic magmatism (e.g., Giles complex) was accompanied by bimodal volcanism and dike swarms at ~1.08 Ga. Subsequently, the region was overprinted by granulite facies metamorphism at ~1.06 Ga.

In our proposed reconstruction, there is a large gap between Grenville belts in Laurentia and Australia. The Oaxaca terrane of Mexico (Fig. 2B) could have occupied this gap prior to Phanerozoic displacement on the Mojave-Sonora megashear (Anderson and Silver, 1979). The location and facing direction of the Paleozoic miogeocline (west of Oaxaca basement) is compatible with an original position farther to the northwest (Ruiz et al., 1988), where it could have been part of a continuous rift margin that rimmed North America (Stewart et al., 1984). This restoration implies a continuous Grenville orogen, consistent with cessation of convergent tectonism in both continents after 1.1 Ga.

Northwest-directed contraction in Laurentia was accompanied by northeast-directed intraplate extension resulting in emplacement of mafic dike swarms, sedimentation in failed rifts, and formation or reactivation of northwest-trending extensional faults. Intracratonic deformation in Australia at this time was similar in style. Northwest-trending extensional faults were active along the Torrens Hinge zone between 1.3 and 1.0 Ga (Myers et al., 1996). Mafic dikes, similar in age to the Arizona 1.1 Ga diabase dikes are represented by the Stuart and Kulgera dikes of central Australia (Camacho et al., 1991).

Rift History: Breakup of Rodinia 800–550 Ma

Conflicting lines of evidence suggest fragmentation of Rodinia at either ca. 800–700 Ma or 600–550 Ma. The earlier time of initial continental separation is supported by geologic evidence for the development of rift basins with immature clastic sediments and abundant mafic magmatism on both continents (Fig. 2C; Centralian Superbasin; Walter and Veevers, 1997; Windermere Supergroup and equivalents; Ross, 1991). New paleomagnetic data from the Mundine Well dikes of Australia (Wingate and Giddings, 1999) also suggest that rifting between the western United States and Australia began before 755 Ma.

PALEOMAGNETIC CONSTRAINTS

Paleomagnetic data provide another way to test the competing Proterozoic plate reconstructions. However, the scarce Proterozoic data set with precise ages and demonstrably primary magnetizations does not unequivocally validate either the SWEAT or the AUSWUS reconstruction.

Paleoproterozoic (2.5–1.6 Ga) data are sparse for North America. Nevertheless, using a reconstruction intermediate between SWEAT and AUSWUS (Ross et al., 1992), Idnurm and Giddings (1995) noted a broad agreement between the Australian and North American APW paths over the entire interval 1.7–0.7 Ga. This conclusion must be viewed with caution because of the overall lack of well-dated primary paleomagnetic poles between 1.7 and 1.5 Ga and 0.9 and 0.7 Ga, especially for Laurentia.

A comparison of Mesoproterozoic poles from Australia and North America qualitatively favors the AUSWUS model. With some uncertainties, the APW path

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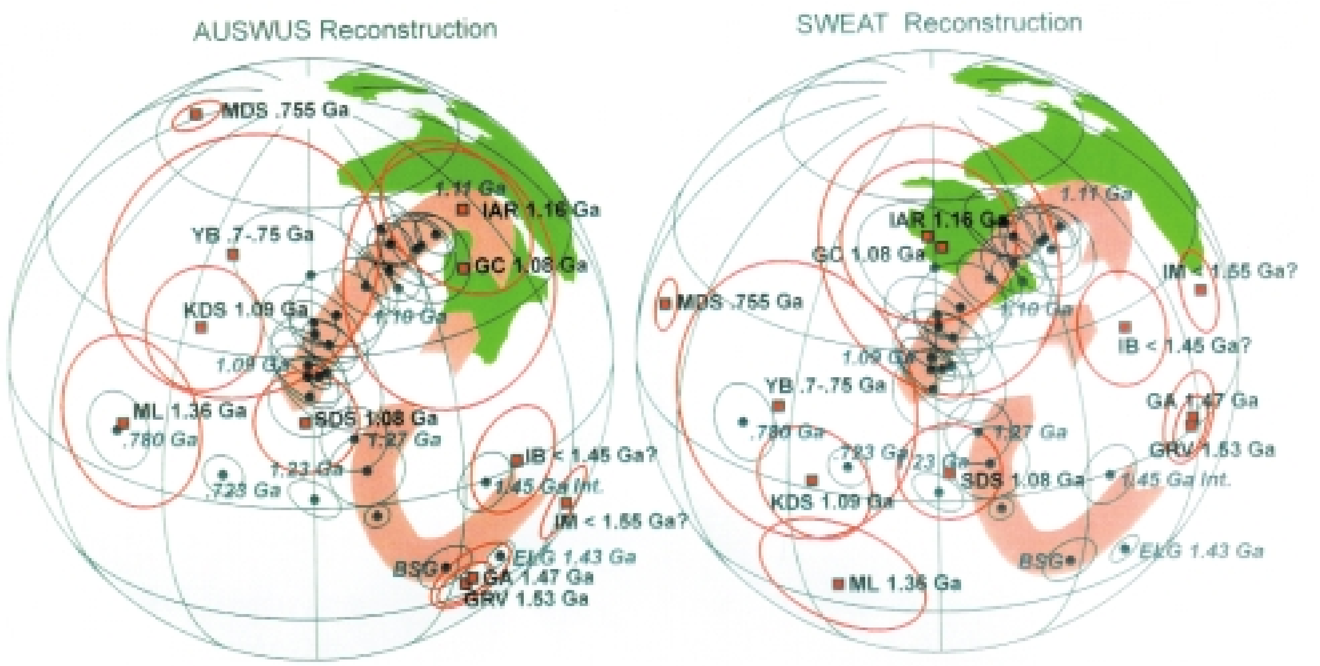

Figure 3. Orthogonal global projections centered on 30°N, 180°E showing comparison of the paleomagnetic poles from Australia with those from North America for the AUSWUS and SWEAT reconstructions. In each projection, Australia and the Australian paleomagnetic poles are rotated into present-day North American coordinates using Euler poles discussed in Table A (see footnote 1). The thick pink lines show the overall track of the ca. 1.45 to 1.1 Ga apparent polar wander path for North America. Solid circles and thin lines denote Paleomagnetic poles for North America and their 95% confidence limits; red squares and red heavy lines denote Australian poles and 95% confidence limits. Blue lettering gives age limits for segments of the North American path; black lettering gives Australian poles and ages. Pole locations for the 1.25 to 1.08 Ma part of the North American apparent polar wander path are tabulated in Harlan et al. (1994); sources for the ca. 1450 Ma poles are from Harlan and Geissman (1998). The 780 Ma North American poles are from Park et al. (1995), as slightly modified by Harlan et al. (1997). The 723 Ma North American pole is from the Global Paleomagnetic Online Database. Sources and rotated coordinates for the Australian poles are in Table A (see footnote 1).

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for North America for the intervals 1450–1400 Ma and 1110–1090 Ma is well defined. Most Australian poles for this period (Fig. 3; Table A[1]), although of lower overall quality than their North American counterparts, match the geometry of the North American APW path reasonably well in the AUSWUS reconstruction (Fig. 3). In contrast, the fit of the 1.4–1.1 Ga Australian poles in the SWEAT configuration is less compelling; only one Australian pole (IAR, ca. 1.16 Ga; Fig. 3) is consistent with the North American APW path. Older paleomagnetic poles for Australia (poles GA-1.47 Ga and GRV-1.53 Ga) are in reasonable agreement in either configuration, but there are no high-quality North American data older than about 1.45 Ga with which these can be compared.

Neoproterozoic (ca. 800 to 700 Ma) paleomagnetic results from Laurentia and Australia are less informative and do not distinguish between the models. The SWEAT reconstruction arguably shows better consistency of the Australian Yilgarn B pole with available Neoproterozoic poles from North America (780 and 730 Ma; Fig. 3). However, the Yilgarn B pole is poorly determined and questionable in age. A new high-quality paleomagnetic pole for the 755 Ma Mundine Well dike swarm of western Australia (Wingate and Giddings, 1999) is discordant with the Laurentian Neoproterozoic poles in either the SWEAT or AUSWUS reconstructions (Fig. 3). These data suggest that a 50°-wide ocean existed between the two continents at 755 Ma.

CONCLUSIONS

We view the southern margin of Laurentia as a long-lived (1.8–1.0 Ga) Cordilleran-type convergent margin involving several orogenic events or tectonic pulses. This interpretation links a sequence of southward-younging belts along the evolving margin and leads to looking for their continuations outside present-day Laurentia. The approach of using the integrated tectonic evolution of an orogenic system for Precambrian plate reconstructions is a powerful test of the supercontinent concept. We note similar 1.8–0.8 Ga rocks and tectonic histories in Australia, southern Laurentia, and Baltica. In evaluating these three key segments of the global supercontinent puzzle, we argue that the AUSWUS model provides a better explanation for the geologic and paleomagnetic data than does the SWEAT reconstruction. In view of the uncertainty regarding the configuration, timing, and existence of the Rodinian supercontinent, there is a continuing need to test alternate Proterozoic plate reconstructions.

[1] GSA Data Repository item 8882, Table A, Australia Paleomagnetic Poles used in AUSWUS and SWEAT Reconstructions, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301 or at www.geosociety.org/pubs/drpint.htm.

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Kenneth N. Weaver
Secretary NEGSA
Maryland Geological Survey
2300 St. Paul Street • Baltimore, MD 21218
Telephone: (410) 554-5532 • Fax: 410-554-5502 • E-mail: kweaver438@aol.com