# Late Neoproterozoic 40° intraplate rotation within Australia allows for a tighter-fitting and longer-lasting Rodinia

Zheng-Xiang Li[1] and David A.D. Evans[2]

[1]The Institute for Geoscience Research (TIGeR), Department of Applied Geology, Curtin University, GPO Box U1987, Perth, WA 6845, Australia

[2]Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06520-8109, USA

## ABSTRACT

**Previous paleomagnetic work has appeared to demand the breakup of southwest United States–East Antarctic (SWEAT) type Rodinia reconstructions before ca. 750 Ma, significantly earlier than the stratigraphic record of rift-drift transition between 715 Ma and 650 Ma. Here we reanalyze Australian paleomagnetic and regional tectonic data to produce a model in which the Precambrian Australian continent had a slightly different configuration before the breakup of Rodinia. A cross-continental megashear zone developed along the Paterson and Petermann orogens at ca. 650–550 Ma, during or after the breakup of Rodinia, manifested as an ~40° clockwise rotation of the South and West Australian cratons relative to the North Australian craton around a vertical axis in Central Australia. This model reconciles major paleomagnetic discrepancies within Australia, and allows for a longer lifespan of SWEAT-like reconstructions of Rodinia that are consistent with the Neoproterozoic stratigraphic records of Australia and Laurentia.**

## INTRODUCTION

The breakup processes of the Neoproterozoic supercontinent Rodinia likely played key roles in the occurrence of global glaciations (Hoffman and Schrag, 2002; Li et al., 2004) and the rapid evolution of complex life on Earth (McMenamin and McMenamin, 1990). However, no consensus has yet been reached regarding the configuration and evolution history of the supercontinent. At the core of the debate is how Australia and East Antarctica were connected to western Laurentia; competing models include the classic southwest United States–East Antarctic (SWEAT) connection (Moores, 1991), the Australia–southwest United States (AUSWUS) model (Karlstrom et al., 1999), the Australia–northwest Mexico (AUSMEX) juxtaposition (Wingate et al., 2002), the "missing-link" model of south China between Australia and western Laurentia (Li et al., 1995), and an entirely distinct configuration with no proximity between Australia and western Laurentia (Evans, 2009). There is also a longstanding controversy regarding the timing of the breakup events, particularly that between Australia–East Antarctica and Laurentia. Paleomagnetic data from Western Australia appeared to demand the breakup of the SWEAT-type reconstructions, if valid, before ca. 750 Ma (Wingate and Giddings, 2000), a conclusion adapted by most researchers (e.g., Li et al., 2008a). However, the stratigraphic record in southeast Australia indicates a rift-drift transition between the Sturtian glacial deposits (ca. 715 Ma; Hoffman and Li, 2009; Macdonald et al., 2010) and the overlying sag-phase deposits (Powell et al., 1994) that were recently dated at 680 ± 23 Ma (Th–U–total Pb age of authigenic monazite; Mahan et al. 2010). This geologically based age estimation from Australia agrees with those from south China, where continental rifting finished at around the time of the Nantuo glaciation (Wang and Li, 2003), dated at between ca. 650 Ma and 635 Ma (Hoffman and Li, 2009, and references therein), and from that era or possibly later in western Laurentia (Ross, 1991; Colpron et al., 2002; Fanning and Link, 2004).

In addition, there is a lack of agreement among some late Precambrian paleomagnetic poles within Australia. For example, two high-quality 1.07 Ga poles from different regions in Australia are ~35° apart, leading to a dramatically different paleogeographic reconstruction of the Australian continent (Schmidt et al., 2006). In this paper we present a model that reconciles three pairs of discrepant paleomagnetic poles from Australia by invoking a geologically feasible, cross-continental, late Neoproterozoic megashear zone. We further examine the implications of this new interpretation to the assembly, configuration, and breakup history of Rodinia.

## NEOPROTEROZOIC CROSS-AUSTRALIA MEGASHEARING THAT RECONCILES THREE PAIRS OF PALEOPOLES

Figure 1 shows three pairs of similar-aged but discrepant Precambrian paleomagnetic poles from Australia (see Table DR1 in the GSA Data Repository[1]). The best dated among them are the two 1.07 Ga poles: one from the Bangemall Basin sills in the West Australia craton (Wingate et al., 2002), and the other from the Alcurra dikes and sills (formerly known as the Kulgera dikes) in the northern Musgrave Block of Central Australia (part of the North Australia

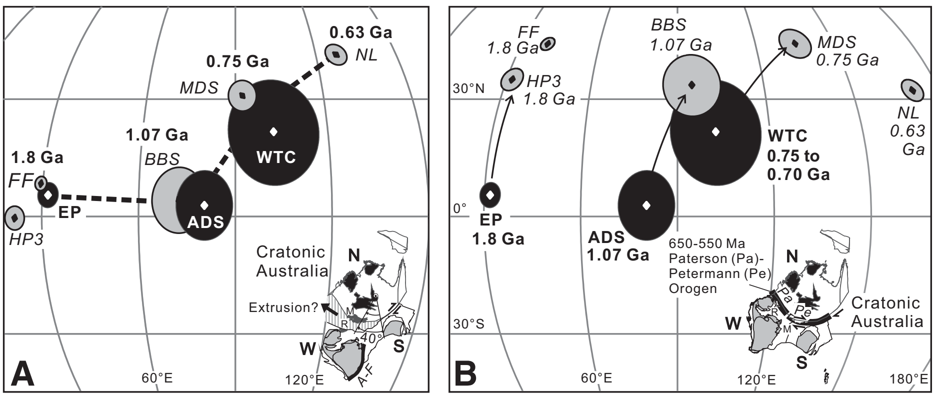


**Figure 1. A: Restoration of an intraplate vertical-axis rotation (Euler parameters 20°S, 135°E, rotation angle 40°) brings paired Australian Precambrian paleomagnetic poles to good agreements. B: Same paired poles in present Australian configuration showing systematic discrepancies between them. Paleopoles are shaded according to their corresponding continental blocks shown on map. N—North Australian craton, W—West Australian craton, S—South Australian craton, A-F—Albany-Fraser orogen. For pole abbreviations and list, see the Data Repository (see footnote 1).**

[1]GSA Data Repository item 2011030, list of Precambrian paleomagnetic poles shown in Figures 1 and 2, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

craton; Schmidt et al., 2006). The position of this latter pole is consistent with the pole position given by the potentially correlative Stuart dikes in the Arunta Block of the North Australia craton (Idnurm and Giddings, 1988). The ~35° separation between the Bangemall and Alcurra poles has been dealt with in different ways with distinct tectonic and paleogeographic implications. Wingate et al. (2002) discredited the reliability of the initial Kulgera pole (Camacho et al., 1991), which was subsequently upgraded to the higher quality Alcurra pole (ADS in Fig. 1; Schmidt et al., 2006). Using their Bangemall Basin sills pole (BBS in Fig. 1), Wingate et al. (2002) concluded that neither the SWEAT nor the AUSWUS connections could have existed at 1.07 Ga. Schmidt et al. (2006), alternatively, invoked major plate convergence between the three Australian cratons (i.e., the North, West, and South Australian cratons in Fig. 1) after 1.07 Ga to account for the discrepancy, implying a much later assembly of Australia. However, the geological record shows that major orogenic events between the West and South Australian cratons along the Albany-Fraser orogen finished by ca. 1.14 Ga (Clark et al., 2000), and stratigraphic coherence of the ca. 800–600 Ma Centralian superbasin (Walter et al., 1995) rules out models of Australian amalgamation by closure of wide late Neoproterozoic ocean basins.

The second pair of similar-aged but discrepant paleopoles from different regions of Australia comprises the overprint pole in the Hamersley Basin of the West Australian craton (HP3 in Fig. 1; Li et al., 2000) related to the ca. 1.8 Ga Capricorn orogeny (Cawood and Tyler, 2004), and the ca. 1.8 Ga pole from the Elgee and Pentecost Formations of the North Australian craton (EP in Fig. 1; Li, 2000b; Schmidt and Williams, 2008). The third pair consists of poles from the 755 Ma Mundine Well dikes in the West Australian craton (MDS pole; Wingate and Giddings, 2000) and the Walsh Tillite cap carbonate, from the North Australian craton (WTC pole; Li, 2000a) (Fig. 1), although precise geological constraints on the age of the Walsh Tillite are still lacking, and correlations with other postglacial cap carbonates in Australia are debated (Grey and Corkeron, 1998).

Figure 1A shows a much improved matching between the three pairs of paleopoles through rotating the West and South Australian cratons around an Euler pole in Central Australia (20°S, 135°E, 40° counterclockwise rotation; presented in round numbers). We note that the WTC pole and the NL pole, from the ca. 630 Ma Nuccaleena Formation cap carbonate unit over the ca. 635 Ma Marinoan glacial deposits in South Australia (Schmidt et al., 2009), are significantly apart in both configurations, but come closer together in our tectonic restoration. Whether this provides definitive support of a Sturtian-aged Walsh Tillite (Li, 2000a), or implies additional local tectonic corrections to align the WTC pole with its alternative potential NL pairing (Grey and Corkeron, 1998), requires further study.

The better matching of the three pairs of poles from northern and southern-western Australia implies that the configurations of the Australian cratons were different prior to ca. 700 Ma (Fig. 1A) relative to their present configuration (Fig. 1B). The North and West Australian cratons were possibly in their restored configuration as shown in Figure 1A since the time of craton amalgamation ca. 1.8 Ga (Li, 2000b; Payne et al., 2009). Together, they joined the South Australia craton (and adjacent parts of East Antarctica) by ca. 1.2 Ga through continental collision along the Albany-Fraser orogen (A–F in Fig. 1A). The Proterozoic reconstruction of Australia proposed herein accounts for a large portion of the rotation hypothesized by Giles et al. (2004) and Betts et al. (2007), in order to restore quasi-linear elements of Paleoproterozoic–Mesoproterozoic geology between the Mount Isa and Curnamona blocks. Convergence across the Albany-Fraser orogen can account for the first stage of such intra-Australian relative motion ca. 1.2 Ga. If our interpretation is correct, it requires the existence of a subsequent cross-continental dextral-transpressional shear zone between northern and southern-western Australia after 750–700 Ma.

## GEOLOGICAL EVIDENCE FOR A NEOPROTEROZOIC CROSS-CONTINENTAL OROGEN IN AUSTRALIA

Geologists have long noticed the occurrence of late Neoproterozoic orogenic events, named the Paterson orogeny in Western Australia and the Petermann orogeny in Central Australia (Myers et al., 1996). However, the kinematics and significance of such intracratonic orogenies have been enigmatic. They occurred after the termination of Adelaidean rifting ca. 700 Ma (Preiss, 2000), and are characterized by intracontinental dextral shearing (Aitken et al., 2009; Austin and Williams, 1978). Major metamorphic, magmatic, and shearing events occurred during both the Paterson and the Petermann orogenies (Fig. 1B). The tectonic events are constrained to ca. 650–550 Ma, as evidenced by granitic intrusions and $^{40}Ar$-$^{39}Ar$ muscovite ages in the Rudall Complex of the central Paterson orogen (R in Fig. 1; Durocher et al., 2003), and 600–550 Ma ages for eclogite facies metamorphism, cooling, and foreland basin deposition in and around the Musgrave Block of the Petermann orogen (M in Fig. 1; Aitken et al., 2009; Camacho, 2002; Raimondo et al., 2010).

We propose here that this vast intracratonic orogen was formed by the ~40° clockwise rotation of the combined West and South Australian craton relative to the North Australian craton during the late Neoproterozoic (650–550 Ma), as implied by the paleomagnetic results (Fig. 1). The origin of this rotation may have been the collision of Neoproterozoic India with the western margin of Australia at the time (Collins, 2003; Li et al., 2008a). In the Petermann orogen the upper crust was shortened by more than 100 km (Raimondo et al., 2010). However, crustal extrusion (escape tectonics; Bagas, 2004) may also have played a role in accommodating as much as 600 km crustal shortening predicted for the Paterson orogen and its possible continuation beneath the Paleozoic Canning Basin.

## IMPLICATIONS FOR THE CONFIGURATION AND EVOLUTION OF THE SUPERCONTINENT RODINIA

A revised pre–650 Ma configuration for Australia as shown in Figure 1A has implications for the formation, configuration, and breakup history of Rodinia, not only because of the altered shape for Australia–East Antarctica, but also because such a configuration alters the shape of the Australian apparent polar wander path (APWP), which is used for reconstructing Rodinian history.

The now-restored 1070 Ma pole positions for Australia place Australia–East Antarctica at paleolatitudes similar to those of Laurentia, but disallow SWEAT-, AUSWUS-, or AUSMEX-type reconstructions for that time. However, as shown in Figure 2, the revised Australian APWP no longer demands the breakup of a SWEAT-type configuration before ca. 750 Ma, as previously thought (Li et al., 2008a; Wingate and Giddings, 2000). In such a configuration, the 755 ± 3 Ma MDS pole from the West Australia craton, corrected for the Neoproterozoic rotation, is between the 780 Ma and 720 Ma pole positions for Laurentia, and the WTC pole from the cap dolomite of the Walsh Tillite in the North Australia craton overlaps with the 720 Ma Laurentian pole (Figs. 2A, 2B). The significant distance between the 615 ± 2 Ma Laurentian Long Range Dikes pole (LRD in Fig. 2A) and the similar-aged EM and NL poles from Australia (see the Data Repository) suggests that Rodinia had broken apart by ca. 630–620 Ma. The initial breakup of Rodinia is therefore defined between 720 Ma and 630 Ma, consistent with the stratigraphic estimation of 715–650 Ma. The 650–550 Ma dextral transpressional shear movement along the Paterson-Petermann orogen in Australia (Fig. 2C) occurred during this breakup process, as well as the early stages of eastern Gondwanaland assembly (Meert, 2003). The relative position between Australia–East Antarctica and Laurentia in this configuration is similar to that of the IGCP440 (International Geoscience

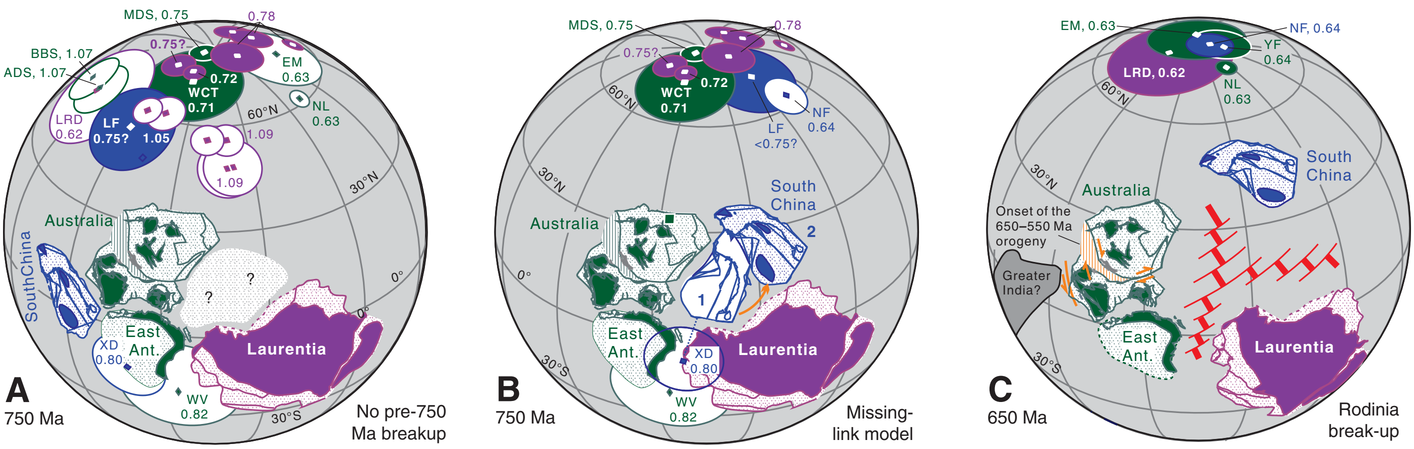


**Figure 2. Possible syn-Rodinia and post-Rodinia models incorporating Australian reconstruction presented herein. Pole ages are indicated; for pole abbreviations and list, see the Data Repository (see footnote 1). A: Revised Australia–East Antarctica–Laurentia fit with southern Australian and East Antarctica (Ant.) cratons rotated to North Australian craton as in Figure 1, and combined Australia–East Antarctica assemblage rotated to Laurentia using Euler rotation (44°N, 143°E, 104°). The 1.07 Ga poles from Australia are significantly displaced from expected Laurentian pole of that age (between the 1.09 Ga and 1.05 Ga poles), implying that configuration could not have existed at that time. The ca. 750–720 Ma poles between continents agree in this configuration. South China is rotated relative to Laurentia using Euler rotation (00°N, 353°E, 156°). Laurentia is reconstructed to paleogeographic grid using Euler rotation (42°N, 184°E, –131°). B: As in A, but with south China placed between Australia and Laurentia for 900–800 Ma interval (position 1, with no shading) in "missing-link" configuration, using Euler rotation parameters (39°N, 166°E, –157°) relative to Laurentia. In this configuration available ca. 800 Ma poles are concordant, but ca. 750 Ma poles imply that south China should have rotated to a new position by that time (position 2, shaded; Euler rotation relative to Laurentia: 17°N, 164°E, –101°). C: A 650 Ma reconstruction following option presented in B, illustrating onset of right-lateral transpressional tectonism along Paterson-Musgrave orogen between Rodinia breakup and Gondwana assembly. Euler reconstructions to paleogeographic grid: Laurentia (35°N, 166°W, –143°), North Australia (11°N, 26 °E, 46°), and south China (46°, 145°, 168°).**

Programme, Rodinia assembly and breakup project) reconstruction in Li et al. (2008a).

The position of the South China Block in this reconstruction is still uncertain. We show here two possible options. In Figure 2A, we place the South China Block in a position that minimizes the distance between its ca. 800 Ma (XD) and ca. 750 Ma (LF) poles (see the Data Repository) and corresponding poles for Australia. However, this leaves a gap between Laurentia and Australia and negates south China's geological links with Australia and Laurentia (as in Li et al., 2008a, 2008b). Also, the requirement of a post–1070 Ma collision between Australia and Laurentia, as noted herein, requires an unknown, intervening craton bearing that Rodinia-forming orogen. In Figure 2B, south China, which does bear such an orogen (Li et al., 2002), is placed in that gap. In this configuration, resembling the "missing-link" model (Li et al., 1995), the ca. 800 Ma XD pole from south China matches that of the WV pole from South Australia (see the Data Repository), but the ca. 750 Ma LF pole for south China does not match that of the other continents. If we accept such a configuration for 900–800 Ma, south China would need to have rotated out of that space by 750 Ma (Fig. 2B). By ca. 650 Ma, Rodinia breakup in this sector of the supercontinent had been completed, and the transcontinental megashear began to consolidate the Australian continent as it is now constructed (Fig. 2C).

## CONCLUSIONS

Both geological evidence and paleomagnetic data from Australia suggest cross-continental dextral shearing and shortening between the combined South and West Australian cratons and the North Australian craton along the Paterson-Petermann orogen at 650–550 Ma. Restoration of the Australian continent prior to this tectonic movement leads to more coherent segments of APWP for Australia. This new data set, when compared with coeval paleopoles from Laurentia, suggests that a modified SWEAT-type configuration in Rodinia could have existed after 1070 Ma (from ca. 900 Ma; Li et al., 2008a), but the fragmentation of the supercontinent likely started after ca. 720 Ma, with major continental dispersion having occurred by 650 Ma. This conclusion resolves the long-standing contradiction between paleomagnetic and stratigraphic analyses on the timing of Rodinia breakup. Two alternative positions for the South China Block in Rodinia are examined in light of this new analysis. A position adjacent to Western Australia is paleomagnetically viable, but it leaves a gap between Australia and Laurentia and ignores geological links as argued by some (Li et al., 2008a, 2008b). Alternatively, south China can be placed between Australia and Laurentia, similar to the "missing-link" model. It is suggested that the ~40° clockwise rotation of the combined South and West Australian cratons relative to the North Australian craton, in an intraplate setting, occurred at 650–550 Ma, after the final phase of the breakup of Rodinia, and during Gondwanaland assembly.


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Wingate, M.T.D., Pisarevsky, S.A., and Evans, D.A.D., 2002, Rodinia connections between Australia and Laurentia: No SWEAT, no AUSWUS?: Terra Nova, v. 14, p. 121–128, doi: 10.1046/j.1365-3121.2002.00401.x.

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Table DR1. List of paleomagnetic poles shown in Figures 1 and 2.

| *ROCKNAME* | *POLE NAME* | *POLE LAT.* | *POLE LONG.* | *DP* | *DM* | *AGE ESTIM. (MA)* | *AUTHORS* | *YEAR* | *JOURNAL* | *VOL.* | *PAGES* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **NORTH AUSTRALIA** | | | | | | | | | | | |
| Elgee-Pentecost combined | EP | 5.4 | 31.8 | 2.3 | 4.5 | ~1800 | Schmidt, P.W., Williams, G.E. | 2008 | Precambrian Res. | 167 | 267-280 |
| | | | | | | | Li, Z.X. | 2000 | Geophys. J. Int. | 142 | 173-180 |
| Mt. Isa Dolerite Dykes | IAR | -9.5 | 31.1 | 17.4 | 17.4 | 1140 ± 1 | Tanaka, H., Idnurm, M. | 1994 | Precambrian Res. | 69 | 241-258 |
| Alcurra dykes+sills | ADS | 2.8 | 80.4 | 7.2 | 10.7 | 1085-1066 | Schmidt et al. | 2006 | Geophys. J. Int. | 167 | 626-634 |
| Walsh Tillite cap dolomite | WTD | 21.5 | 102.4 | 13.7 | 13.7 | 750-700 | Li, Z.X. | 2000 | Precambrian Res. | 100 | 359-370 |
| **SOUTH+WEST AUSTRALIA** | | | | | | | | | | | |
| Frere Formation | FF | 45.2 | 40.0 | 1.3 | 2.4 | ~1800 | Williams, G.E. et al. | 2004 | Precambrian Res. | 128 | 367-383 |
| Hamersley Province overprint | HP3 | 35.3 | 31.9 | 3.0 | 3.0 | ~1800 | Li, Z.X. et al. | 2000 | MERIWA Project No. M242Report | 199 | 216 pp. |
| Bangemall Sills | BBS | 33.8 | 95.0 | 8.3 | 8.3 | 1070 ± 6 | Wingate, M.T.D. et al. | 2002 | Terra Nova | 14 | 121-128 |
| Wooltana Volcanics | WV | -62.0 | 142.0 | 16.0 | 18.0 | ~820 | McWilliams, M.O., McElhinny, M.W. | 1980 | J. Geol. | 88 | 1-26 |
| Mundine Well Dykes | MDS | 45.3 | 135.4 | 4.1 | 4.1 | 755 ± 3 | Wingate, M.T.D., Giddings, J.W. | 2000 | Precambrian Res. | 100 | 335-357 |
| Yaltipena Formation | YF | 44.2 | 172.7 | 5.9 | 11.4 | ~640 | Sohl, L.E. et al. | 1999 | Geol. Soc. Amer. Bull. | 111 | 1120-1139 |
| MEAN Elatina Formation | EM | 49.9 | 164.4 | 13.5 | 13.5 | ~635 | Embleton,B.J.J., Williams,G.E. | 1986 | Earth Planet. Sci. Lett. | 79 | 419-430 |
| | | | | | | | Schmidt,P.W. et al. | 1991 | Earth Planet. Sci. Lett. | 105 | 355-367 |
| | | | | | | | Schmidt,P.W., Williams,G.E. | 1995 | Earth Planet. Sci. Lett. | 134 | 107-124 |
| | | | | | | | Sohl,L.E. et al. | 1999 | Geol. Soc. Amer. Bull | 111 | 1120-1139 |
| Nuccaleena Fm | NL | 32.3 | 170.8 | 2.2 | 3.9 | ~630 | Schmidt, P.W. et al. | 2009 | Precambrian Res. | 174 | 35-52 |
| **SOUTH CHINA** | | | | | | | | | | | |
| Xiaofeng Dykes | XD | 13.5 | 91.0 | 10.5 | 11.3 | 802 ± 10 | Li, Z.X. et al. | 2004 | Earth Planet. Sci. Lett. | 220 | 409-421 |
| Liantuo Formation | LF | 4.4 | 161.1 | 12.9 | 12.9 | 750-660 | Evans, D.A.D. et al. | 2000 | Precambrian Res. | 100 | 313-334 |
| Nantuo Formation | NF | 0.2 | 151.2 | 5.4 | 7.5 | ~640 | Zhang, Q.R., Piper, J.D.A. | 1997 | Precambrian Res. | 85 | 173-199 |
| **LAURENTIA** | | | | | | | | | | | |
| Chengwatana Volcanics | 1.09 | 30.9 | 186.1 | 6.5 | 10.3 | 1095 ± 2 | Kean, W.F. et al. | 1997 | Geophys. Res. Lett. | 24 | 1523-1526 |
| Portage Lake Volcanics | 1.09 | 26.7 | 178.0 | 3.5 | 6.3 | 1095 ± 3 | Hnat, J.S. et al. | 2006 | Tectonophysics | 425 | 71-82 |
| Cardenas Basalts and Intrusions | 1.09 | 32.0 | 185.0 | 6.8 | 9.3 | 1091 ± 5 | Weil, A.B. et. al. | 2003 | Tectonophysics | 375 | 199-220 |
| Lake Shore Traps | 1.09 | 22.2 | 180.8 | 4.5 | 4.5 | 1087 ± 2 | Diehl, J.F., Haig, T.D. | 1994 | Canad. J. Earth Sci. | 31 | 369-380 |
| Freda Sandstone | 1.05 | 2.2 | 179.0 | 3.0 | 5.9 | ~1050 | Henry, S.G. et al. | 1977 | Canad. J. Earth Sci. | 14 | 1128-1138 |
| Nonesuch Shale | 1.05 | 7.6 | 178.1 | 3.9 | 7.8 | ~1050 | Henry, S.G. et al. | 1977 | Canad. J. Earth Sci. | 14 | 1128-1138 |
| Tsezotene Sills Combined | 0.78 | 1.6 | 137.8 | 5.0 | 5.0 | 778 ± 2 | Park, J.K. et al. | 1989 | Canad. J. Earth Sci. | 26 | 2194-2203 |
| Tobacco Root Dykes - B | 0.78 | 14.6 | 127.0 | 9.2 | 11.6 | 775 ± 3 | Harlan, S.S. et al. | 2008 | Precambrian Res. | 163 | 239-264 |
| Christmas Lake Dyke | 0.78 | 7.4 | 137.0 | 4.4 | 8.3 | 774 ± 4 | Harlan, S.S. et al. | 1997 | USGS Prof. Paper | 1580 | 16 pp. |
| Mount Moran Dyke | 0.78 | 11.6 | 148.9 | 5.1 | 10.2 | 775 ± 10 | Harlan, S.S. et al. | 1997 | USGS Prof. Paper | 1580 | 16 pp. |
| Uinta Mountain Group | 0.75? | 0.8 | 161.3 | 3.3 | 6.6 | 800-750 | Weil, A.B. et al. | 2006 | Precambrian Res. | 147 | 234-259 |
| Franklin event grand mean | 0.72 | 6.7 | 162.1 | 3.0 | 3.0 | 723 +4/-2 | Denyszyn S.W. et al. | 2009 | Canad. J. Earth Sci. | 46 | 155-167 |
| Long Range Dykes | LRD | 19.0 | 355.3 | 14.8 | 20.5 | 615 ± 2 | Murthy, G.S. et al. | 1992 | Canad. J. Earth Sci. | 29 | 1224-1234 |