Assembly and breakup of the core of Paleoproterozoic–Mesoproterozoic supercontinent Nuna

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ABSTRACT

Idealized conceptual models of supercontinent cyclicity must be tested against the geologic record using pre-Pangean reconstructions. We integrate tectonostratigraphic records and paleomagnetic data from Siberia, Laurentia, and Baltica to produce a quantitative reconstruction of the core of the Nuna supercontinent at 1.9–1.3 Ga. In our model, the present southern and eastern margins of Siberia juxtapose directly adjacent to, respectively, the arctic margin of Laurentia and the Uralian margin of Baltica. Consistent tectonostratigraphic records of the three cratons collectively indicate the history of Nuna's assembly and breakup. According to this reconstruction, the late Mesoproterozoic transition from Nuna to Rodinia appears to have been much less dramatic than the subsequent late Neoproterozoic transition from Rodinia to Gondwana.

INTRODUCTION

Various styles of supercontinental transitions are conjectured (Murphy and Nance, 2005) but not known with certainty due to a lack of precise knowledge of pre-Pangean continental configurations. Global peaks in isotopic ages of igneous rocks appear to indicate the existence of at least two Precambrian supercontinents: Rodinia, which formed ca. 1.0 Ga, and Nuna, which amalgamated ca. 1.9–1.8 Ga (Hawkesworth et al., 2009). The existence of an earlier supercontinent, Kenorland, is questionable, as reviewed by Bleeker (2003), and Reddy and Evans (2009). The configuration of Rodinia remains debatable after nearly two decades of intense investigation (Hoffman, 1991; Dalziel, 1997; Pisarevsky et al., 2003; Meert and Torsvik, 2003; Li et al., 2008; Evans, 2009); nonetheless, initial speculations on the paleogeography of Nuna are beginning to take form (e.g., Zhao et al., 2002).

How can we begin reconstructing a vanished supercontinent? In the frontispiece to his classic book, Du Toit (1937) noted that "Africa forms the key" of Pangea due to its central position surrounded by rifted passive margins developed during breakup. Similarly, recognition of Neoproterozoic rifted margins around Laurentia has led to the widespread consensus that it was near the center of Pangea's predecessor Rodinia (Bond et al., 1984; McMenamin and McMenamin, 1990). Nuna's formation at 1.9–1.8 Ga should have been followed by breakup in the 1.7–1.3 Ga interval (Hoffman, 1989). The Siberian craton is nearly surrounded by Paleoproterozoic–Mesoproterozoic passive margins (Pisarevsky and Natapov, 2003), and thus likely forms the key of the Nuna landmass.

Paleomagnetism remains the only quantitative method to reconstruct pre-Pangean continents to an absolute paleogeographic reference frame. Broad-scale concordance of paleomagnetic latitude estimates with paleoclimatic indicators such as evaporite basins for the past two billion years (Evans, 2006) implies that a paleomagnetic reconstruction of Nuna should be tractable. Quantitative tests of hypothesized Rodinia reconstructions have been made possible due to a well-represented paleomagnetic data set for Laurentia near its center (e.g., Li et al., 2008), but in contrast, paleomagnetic data from Siberia for the Nuna time interval have been entirely lacking. Recently published, high-quality data from Siberia (Wingate et al., 2009; Didenko et al., 2009), however, provide a new starting point for reconstructing cratons around the core of Nuna.

NUNA RECONSTRUCTION

Quality-filtered paleomagnetic poles from Siberia, along with coeval results from Laurentia and Baltica, are listed in Table DR1 of the GSA Data Repository.[1] For ages older than 1.8 Ga, we only compare paleomagnetic data from the closest reconstructed cratonic neighbors, for example Siberia and Slave, rather than distant and likely unconnected cratons, such as Siberia and Superior (cf. Didenko et al., 2009). The highest-quality results from Siberia are from the 1.88–1.86 Ga Akitkan volcanic and sedimentary rocks (Didenko et al., 2009) and the 1.47 Ga Olenëk intrusions (Wingate et al., 2009), both representing the Anabar-Angara subregion of Siberia. The younger poles and virtual geomagnetic poles are rotated to superimpose atop coeval Laurentian data, largely taken from Evans and Pisarevsky (2008), but notably including the combined Zig-Zag Dal–Midsommersø–Victoria Fjord results from Greenland (Table DR1) that imply a Laurentian apparent polar wander (APW) loop at 1.38 Ga (Fig. 1). The older Siberian poles superimpose, upon the same rotation, atop the most central poles within a swath of similarly aged results from the Slave craton (Mitchell et al., 2010) and support a direct, long-lived connection between those blocks. Also shown in Figure 1 are Baltica in the 1.8–1.2 Ga NENA (northern Europe and North America) configuration (Gower et al., 1990; Buchan et al., 2000; Evans and Pisarevsky, 2008), and more speculative juxtapositions such as proto-SWEAT (southwestern United States and East Antarctica) of Australian cratons against western Laurentia (Betts et al., 2008; Payne et al., 2009), north China adjacent to Siberia (Wu et al., 2005), and SAMBA (South America–Baltica) linking the basement terrains of Baltica, Amazon, and West Africa (Johansson, 2009; see also Bispo-Santos et al., 2008).

Additional Mesoproterozoic data from Siberia, namely from the Kuonamka dikes in the Anabar block (Ernst et al., 2000), although widely used in previous paleomagnetic syntheses (e.g., Meert, 2002; Pesonen et al., 2003), are problematic upon close inspection. The dated Kuonamka dike (ca. 1.50 Ga) bears a paleomagnetic remanence direction that is distinct from others correlated into the same swarm by azimuthal trend. The large discrepancy between that lone direction and the more reliable pole from the nearly coeval (1.47 Ga) Olenëk intrusions (Wingate et al., 2009) suggests that additional study of the Kuonamka dikes, and related intrusions, is warranted. The next younger Siberian paleomagnetic poles form an APW swath that diverges from the Laurentian APW path ca. 1.1 Ga (Fig. 1A; for further illustration, see the Data Repository), implying separation of Siberia prior to that time. Although reliable pre–1.88 Ga poles from Siberia are not available, data from Slave craton and Fennoscandia for 2.1–1.9 Ga are not compatible with our Nuna reconstruction (Fig. 1A; for further illustration, see the Data Repository), implying that the core of the supercontinent assembled ca. 1.9 Ga. Such a result is consistent with the independent evidence from dated orogenic events in Siberia, northern Canada, and Fennoscandia (Lahtinen et al., 2008; Pisarevsky et al., 2008; Corrigan et al., 2009; St-Onge et al., 2009).

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[1]GSA Data Repository item 2011145, paleomagnetic poles and discussion of Euler rotations, 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.

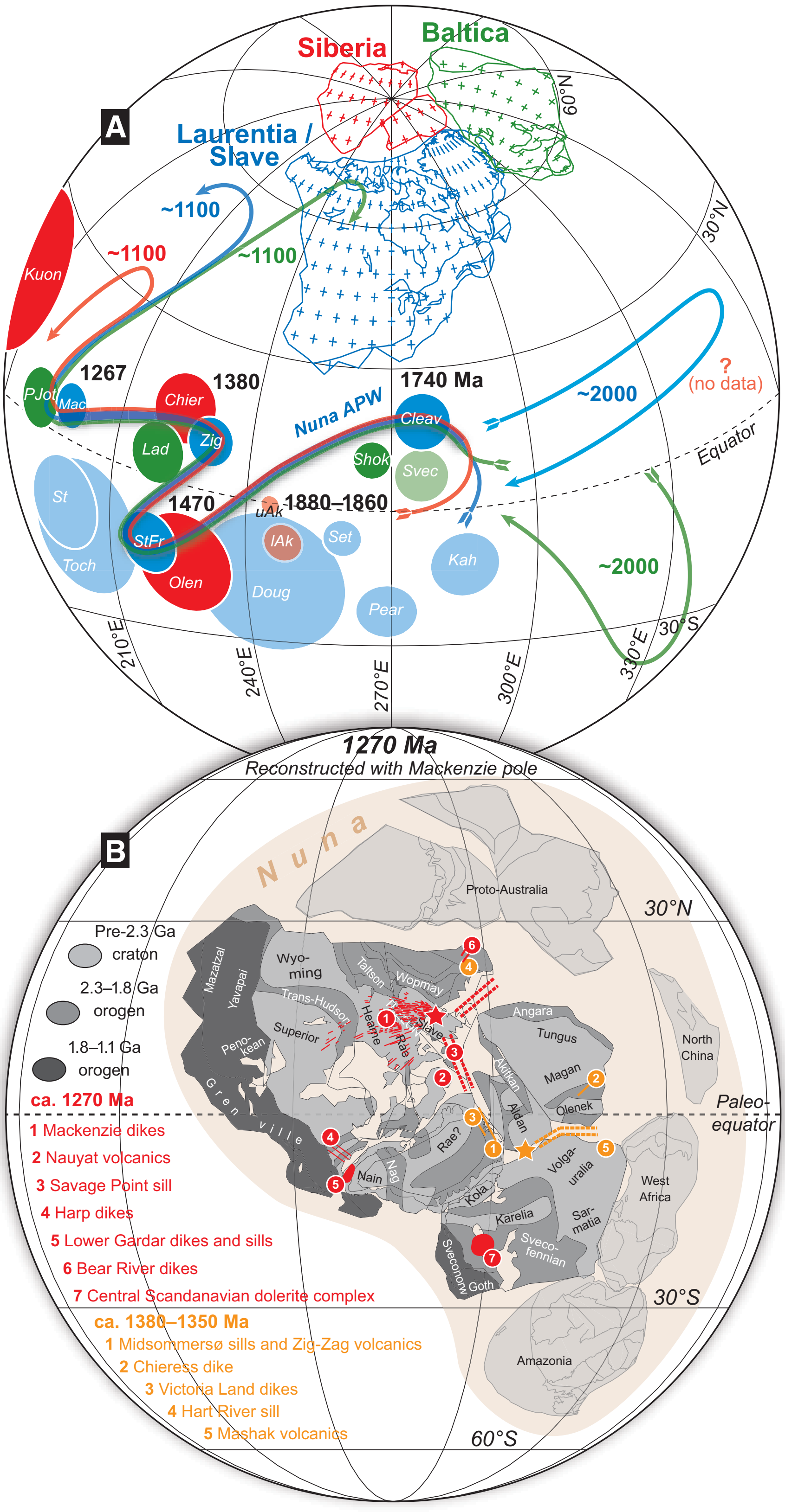

Figure 1. Reconstruction of core of Nuna supercontinent. A: Quality-filtered 1.9–1.3 Ga paleomagnetic poles from Siberia, and coeval results from Laurentia and Baltica (Table DR1; see footnote 1), color-coded by craton (lighter shades represent ages prior to final cratonization), in present North American reference frame (ages in Ma; for Euler parameters and abbreviations, see the Data Repository [see footnote 1]). APW—apparent polar wander. B: Tectonic assemblage map of Nuna, reconstructed to time of initial mid-Mesoproterozoic breakup events. (For further discussion, see the Data Repository.)

Our paleomagnetic analysis is the first to extend putative links between Siberia and present northern Laurentia, back to the more ancient connections between Siberia and only the Slave and Rae Provinces prior to Laurentia's large-scale assembly ca. 1.8 Ga (St-Onge et al., 2006). It allows a tight fit of these terrains in a compact Nuna configuration, not requiring identification of an additional craton to fill an ~1000 km gap as in previous reconstructions (Pisarevsky et al., 2008). It challenges the alternative Proterozoic placement of Siberia along the western margin of Laurentia (Sears and Price, 2003), as well as the hypothesis of Congo–São Francisco along the arctic Laurentian margin from 1.6 to 0.7 Ga (Evans, 2009).

ASSEMBLY AND BREAKUP OF NUNA

The direct juxtaposition of Siberia and northern Laurentia shown in Figure 1 is almost identical to that hypothesized on regional geological grounds by Rainbird et al. (1998); in that synthesis, the Slave craton was postulated to continue into Siberia as the Tungus block, and the Thelon orogen to continue as the Akitkan fold belt. Such correlations are permitted in our reconstruction, but it is also possible that the sedimentary cover of the Canadian archipelago conceals a 1.9 Ga suture between Slave and Tungus (Donskaya et al., 2009). The Aldan shield is a collage of Archean blocks assembled by 1.9 Ga (Rosen et al., 1994; Pisarevsky et al., 2008), via orogenic events that by our reconstruction appear to continue into the Inglefield mobile belt of the northern Baffin Bay region (Nutman et al., 2008). Craton amalgamation of similar age occurred in the proposed adjacent areas of Baltica (Bogdanova et al., 2008; Fig. 1B). Within Laurentia, the Superior and Wyoming cratons represent, respectively, late additions by ca. 1.8 Ga (St-Onge et al., 2006) and 1.75 Ga (Dahl et al., 1999), after which a long-lived accretionary margin wrapped around the nascent landmass (Karlstrom et al., 2001).

Localized extension within Nuna began as early as ca. 1.8–1.7 Ga. In central Laurentia, the Dubawnt Supergroup and related granitoids (Rainbird et al., 2006; Rainbird and Davis, 2007) are a well-preserved and regionally intact example of extension that did not lead to continental separation, an environment that we envisage for the more fragmentary records of the coeval Hekla Sund volcanic rocks in northern Greenland (Pedersen et al., 2002), Ulkan and Urik-Iya grabens in southern Siberia (Pisarevsky et al., 2008), and Cleaver dikes (Irving et al., 2004) plus Bonnet Plume River intrusions (Thorkelson et al., 2001) in northwest Laurentia. Following this episode of localized extension, the enigmatic Racklan and Forward orogenies (Thorkelson et al., 2001; MacLean and Cook, 2004) are interpreted here as intracontinental shortening events within the interior of the supercontinent.

The period 1.5–1.25 Ga signaled the breakup of this core of Nuna. The 1.47 Ga Olenëk intrusions (Wingate et al., 2009) are directly adjacent to the southern Ural Mountains, where early Riphean extension began prior to middle Riphean volcanogenic rifting at 1.35 Ga (Maslov, 2004). That rifting is nearly coeval to precisely dated 1.38 Ga mafic volcanic rocks in northeast Greenland (Upton et al., 2005), the Anabar shield (Ernst et al., 2000), and northwest Canada (Thorkelson et al., 2005). Separation of Siberia probably began at 1.27 Ga, concomitant with emplacement of the giant Mackenzie radiating large igneous province and opening of the Poseidon Ocean (LeCheminant and Heaman, 1989). No Mackenzie-age mafic rocks have yet been identified in southern Siberia (Pisarevsky et al., 2008), but it is conceivable that a three-rift triple junction left the ~120° angle of southern Siberia unscathed by dike intrusion (Fig. 1). Baltica then pivoted clockwise ~90° about a local axis, possibly as late as 1.1 Ga, to reconnect with southeast Greenland in a Rodinia reconstruction (Evans, 2009; Cawood et al., 2010). By 1.05–1.0 Ga, superposition of the Siberian and Laurentian APW paths implies that those cratons were separated by >1000 km (Pisarevsky et al., 2008). Rather than being a promontory of Rodinia (Pisarevsky et al., 2008), we propose that by the end of the Mesoproterozoic Era, Siberia was separate from the Rodinian landmass, either as a stranded continental fragment like Greenland or Madagascar (thus rejoined to the Rodinian plate), or still slowly diverging from Laurentia as part of a separate plate. In the latter case, the 1.05–1.0 Ga Siberian-Laurentian APW concordance would need to be attributed to true polar wander at that time (Evans, 2003; Meert and Torsvik, 2003).

IMPLICATIONS

The tectonic scenario described here, quantitatively acceptable on the basis of paleomagnetic data, documents a profound distinction between the assembly and breakup phases of the Paleoproterozoic–Mesoproterozoic supercontinent Nuna. Its amalgamation occurred via collisions of blocks originally no larger than 2×10^6 km^2 (Superior), yet its breakup took on the more familiar form of widely spaced rifts that separated subcontinent-sized fragments. Insofar as Nuna assembled from an anastomosing set of closely spaced cratonic collisions, it may well be considered as Earth's first true supercontinent (Bleeker, 2003). Comparing our Nuna core reconstruction with the most common depictions of Rodinia (Li et al., 2008), we note rather minimal paleogeographic changes across Earth's first supercontinental cycle, in marked contrast to the dramatic reorganization implied between such Rodinia configurations and the subsequent assembly of Gondwana (Hoffman, 1991). The contrasts between Mesoproterozoic environmental and evolutionary stability (Brasier and Lindsay, 1998) versus Neoproterozoic upheavals in those realms (Butterfield, 2007) are equally striking, and suggest direct links between global tectonics, paleoclimate, and the biosphere at hundred million to billion year time scales.

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A. Paleomagnetic poles shown in Fig. 1

Table DR1. Paleo-Mesoproterozoic paleomagnetic poles from Siberia, and coeval poles from Slave / Laurentia, and Fennoscandia / Baltica.

Craton/rock unit	abbr.	Age (Ma)	Pole(°N,°E)	Rotd-Laur(°N,°E)†	A_{95}(°)	1234567 Q	Ref.
Siberia (Anabar ref. frame)							
Lower Akitkan, Khibelen	lAk	1878±4	–31, 099	–09, 248	4	1111101 6	A
Upper Akitkan, Chaya R.	uAk	1863±9	–23, 097	–01, 245	2	1111101 6	A
Kuonamka dike VGP	Kuon	1503±5	16, 032	17, 171	13	1010100 3	B
Olenëk mafic intrusions	Olen	1473±24	–34, 073	–16, 226	10	1111101 6	C
Chieress dike VGP	Chier	1384±2	–04, 078	15, 224	7	1010101 3	B
Slave / Laurentia							
Seton mean [a]	Set	ca. 1885?		–06, 260	4	0111111 6	D
Kahochella mean [b]	Kah	ca. 1882?		–12, 285	7	0100111 4	D
Douglas Peninsula Fm	Doug	ca. 1880?		–18, 258	14	0010111 4	E
Stark Fm	St	ca. 1875		–15, 215	5	0110110 4	F
Tochatwi Fm	Toch	ca. 1875		–18, 216	11	0111110 4	G
Pearson mean [c]	Pear	1870±4		–22, 269	6	1101111 6	D
Cleaver dikes	Cleav	1740+5/-4		19, 277	6	1111101 6	H
St Francois Mtns	StFr	ca. 1476		–13, 219	6	1111101 6	I
Zig-Zag Dal & intrusions [d]	Zig	1382±2	11, 240	11, 229	3	1111111 7	J,K,L
Mackenzie mean	Mac	1267±2		04, 190	5	1111101 6	M
Fennoscandia / Baltica							
Svecofennian mean	Svec	ca. 1880	41, 233	10, 275	5	1110100 4	N
Shoksha Fm	Shok	1770±12	39, 217	11, 262	7	1111111 7	O
Ladoga intrusions	Lad	1452±12	15, 177	05, 220	6	1111110 6	P
Post-Jotnian mean	PJot	ca. 1265	04, 158	06, 198	4	1111101 6	M

Notes:

[a] mean of results from the Seton, Akaitcho, and Mara Formations, according to the tectonic model of Mitchell et al. (2010).
[b] mean of results from the Kahochella and Peacock Hills Formations (ibid.).
[c] mean of results from the Pearson basalts, Peninsular Sill, and Kilohigok basin (Mara River) sill (ibid.)
[d] mean of 38 VGPs from the Zig Zag Dal basalts, Midsommersø dolerites, and Victoria Fjord dikes.

† Euler rotation parameters to Laurentia in the proposed Paleo-Mesoproterozoic reconstruction: Siberia (Anabar reference frame) 78, 099, +147 (this study); Greenland 67.5, 241.5, –13.8 (Roest and Srivastava, 1989); Baltica 47.5, 001.5, +49 (Evans and Pisarevsky, 2008). Note also an Euler restoration of the Aldan block relative to the Anabar-Angara region of Siberia: 60, 115, 25 (Evans, 2009).

References: A (Didenko et al., 2009), B (Ernst et al., 2000), C (Wingate et al., 2009), D (Mitchell et al., 2010), E (Irving and McGlynn, 1979), F (Bingham and Evans, 1976), G (Evans and Bingham, 1976), H (Irving et al., 2004), I (Meert and Stuckey, 2002), J (Marcussen and Abrahamsen, 1983), K (Abrahamsen and Van der Voo, 1987), L (Upton et al., 2005), M (Buchan et al., 2000), N (Pesonen et al., 2003), O (Pisarevsky and Sokolov, 2001), P (Lubnina et al., 2010).

The seven quality criteria and "Q" factor are described by Van der Voo (1990).

B. Discussion of Euler rotations used in Fig. 1

1. Siberia, Baltica, and Laurentia. The Siberian craton is first restored to its configuration prior to Devonian extension in the Vilyuy graben. Pavlov et al. (2008) quantify a ~20° rotation about a proximal Euler pole to account for early Paleozoic paleomagnetic discrepancies between a northwestern Anabar-Angara block and a southeastern Aldan block. We use the Euler reconstruction parameters of Evans (2009), which were chosen to optimize both early Paleozoic and Meso-Neoproterozoic paleomagnetic data across Siberia. For ages younger than 1.8 Ga, we assume that Siberia, Baltica, and Laurentia were already consolidated cratons (Pisarevsky et al., 2008; Bogdanova et al., 2008; St-Onge et al., 2006). Although the Sarmatian region of Baltica (Elming et al., 2001) and the Yavapai-Mazatzal superterrane of Laurentia (Whitmeyer and Karlstrom, 2007) were still accreting during that time interval, those areas lie comfortably on the external side of our reconstruction so the precise ages of their collisions do not affect our model of the supercontinent's central region.

2. Proto-Australia. The Mawson Continent is restored to North Australia (–18, 134, 51) to match basement geology of the Curnamona and Mt Isa regions, and also to bring 1.74 – 1.59 Ga paleomagnetic poles closer together (Payne et al., 2009). The resulting "Proto-SWEAT" fit honors Mesoproterozoic geological matches between the Transantarctic Mountains and western USA (Goodge et al., 2008), and between South Australia and northwest Canada (Hamilton and Buchan, 2010). Western Australia is restored to North Australia (–20, 135, 40) to account for late Neoproterozoic dextral transpression through the central part of the continent (Li and Evans, 2011). From the North Australian reference frame, all of Proto-Australia restores to Laurentia (31.5, 098, 102.5) as in Payne et al. (2009). In our model, the Mawson Continent rotated clockwise away from western Laurentia during Mesoproterozoic time, colliding with Western Australia along the Albany-Fraser orogen.

3. North China. The craton is restored to Laurentia (11, 196, –24) as in Wu et al. (2005), in order to match paleomagnetic poles from ca. 1770 Ma and ca. 1550 Ma, assuming a long-lived supercontinental fit between the two blocks.

4. West Africa and Amazonia. These cratons are restored to Baltica in an attempt to reproduce quantitatively the sketches of the SAMBA reconstruction by Johansson (2009): West Africa to Baltica (06, 029, –93), Amazonia to Baltica (43, 197, 84). Paleomagnetic tests of these proposed long-lived juxtapositions are in progress.

C. Discordant paleomagnetic poles from ages prior to Nuna assembly

Table DR2. Mid-Paleoproterozoic (2.1–1.9 Ga) paleomagnetic poles from Slave craton and Fennoscandia.

Craton/rock unit	abbr.	Age (Ma)	Pole(°N,°E)	Rotd-Laur(°N,°E)	A_{95}(°)	1234567 Q	Ref.
Slave craton							
Lac de Gras dikes	Lac	ca. 2025		12, 268	7	1111100 5	Q
Rifle Fm (rotated) [a]	Rif-r	1963±6		19, 353	9	1111110 6	R
Fennoscandia							
Kuetsyarvi (lavas only) [b]	Kuet	2058±6	23, 298	–01, 331	7	1011100 4	S
Konchozero sill	Konch	1974±27	–14, 282	–41, 329	10	1011100 3	T

[a] Rifle Formation is restored 12°CCW at the sampling site, according to the conjugate-fault tectonic model described in Mitchell et al. (2010).

[b] Recalculated using only data from lavas, not sediments, by Evans and Pisarevsky (2008). Age from Melezhik et al. (2007).

Rotation parameters as in Table DR1. References: Q (Buchan et al., 2009), R (Evans and Hoye, 1981), S (Torsvik and Meert, 1995), T (Pisarevsky and Sokolov, 1999)

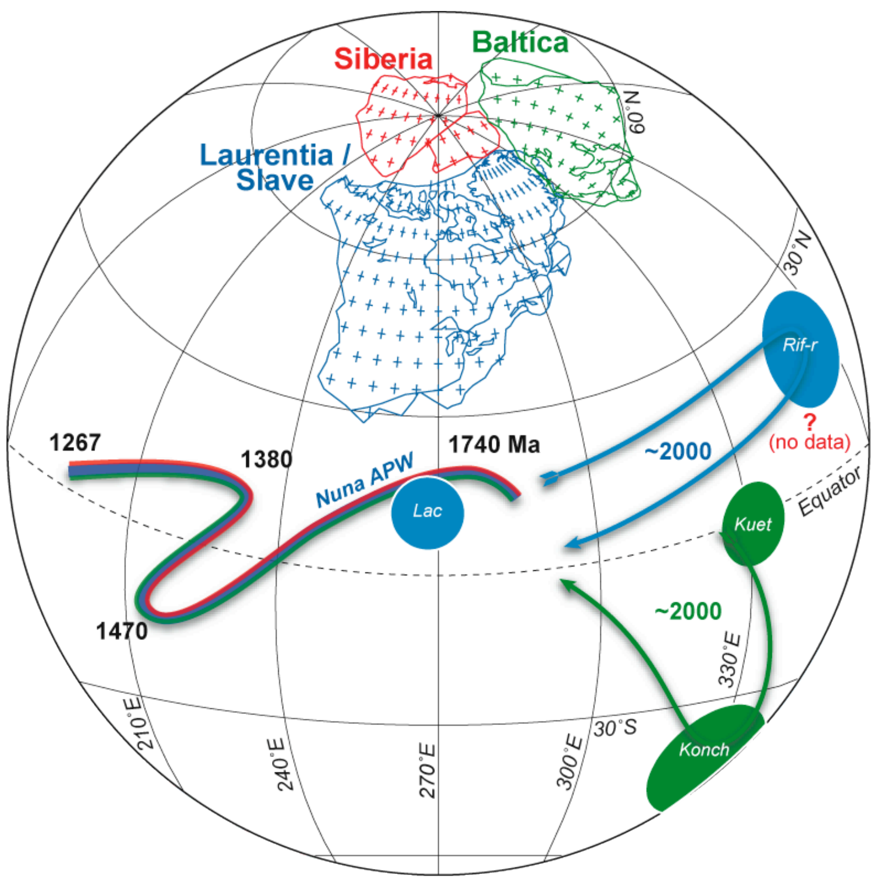

Figure DR1. Mid-Paleoproterozoic poles from Slave craton and Fennoscandia, showing convergent trends of motion, requiring separate plates for those terrains prior to their assembly within Nuna. No reliable data are available from the Tungus terrane of southwestern Siberia, proposed to be originally contiguous with Slave.

D. Discordant paleomagnetic poles from ages after Nuna breakup

Table DR3. Selected Meso-Neoproterozoic (1.2–1.0 Ga) paleomagnetic poles from Siberia, Laurentia, and Baltica.

Craton/rock unit	abbr.	Age (Ma)	Pole(°N,°E)	Rotd-Laur(°N,°E)	A_{95}(°)	1234567 Q	Ref.
Siberia							
Linok Fm	Lin	ca. 1070?	–15, 256	32, 215	8	0111111 6	U
Malgina Fm [a]	Mal	ca. 1070?	–15, 250	30, 209	3	0111111 6	U
Kandyk Fm [a]	Kan	ca. 990	09, 199	–11, 169	4	1110101 5	V
Laurentia							
Abitibi dikes [b]	Abit	1141±1		49, 216	14	1111111 7	W
Logan sills mean	Log	1108±1		49, 220	4	1111101 6	X
Lower Osler volcanics	lOsl	1105±2		43, 195	6	1101101 5	Y
Portage Lake volcanics	Port	1095±3		27, 178	5	1111101 6	Z
Baltica							
Salla dike VGP	Sall	1122±7	71, 113	69, 255	8	1111100 5	AA
Bamble mean	Bam	ca. 1070	–01, 037	–23, 251	15	1010010 3	AB
Laanila dikes	Laa	ca. 1045	02, 032	–26, 243	15	0011100 3	AC

[a] Pole location is rotated to Anabar coordinates using Euler parameters (60, 115, 25) as in Evans (2009).
[b] Recalculated excluding dike A1, which has since been dated as Paleoproterozoic (Halls et al., 2005).

Rotation parameters as in Table DR1. References: U (Gallet et al., 2000), V (Pavlov et al., 2002), W (Ernst and Buchan, 1993), X (Buchan et al., 2000), Y (Halls, 1974), Z (Hnat et al., 2006), AA (Salminen et al., 2009), AB (Meert and Torsvik, 2003), AC (Mertanen et al., 1996).

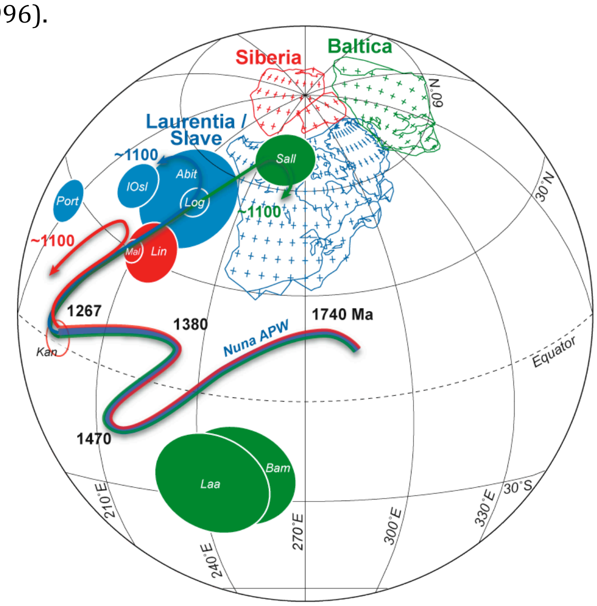

Figure DR2. Meso-Neoproterozoic poles from Siberia, Laurentia, and Baltica, showing divergent trends of motion, requiring separate plates for those terrains. The superposition of Kandyk pole (ca. 990 Ma) atop the 1267 Ma portion of the Nuna APW path is only apparent, as the Kandyk ellipse is projected from the far hemisphere.

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