Tightening the Siberian connection to western Laurentia

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ABSTRACT

Newly available geological and geophysical data tighten the Proterozoic connection between the rifted margins of the northern Siberian craton and western Laurentia, and permit a Siberia-Laurentia-Australia troika, with northern Australia connected to the southern margin of the Siberian craton. The continental assembly is linked by a prominent 2.0–1.8 Ga collisional belt and the ca. 1.3–1.0 Ga Grenville orogen. The reconstruction also aligns a 1.5–1.45 Ga dike/sill swarm that extends from the Wyoming province, through the Belt-Purcell basin, into the northern Siberian craton. Separation of Australia and Siberia may have occurred by the early Neoproterozoic, but separation of Siberia and Laurentia may not have been completed until the Early Cambrian. Continental extension began along the zigzag Siberia-Laurentia rift zone in the early Mesoproterozoic. Rift-related igneous and sedimentary assemblages dated at ca. 1.5, 1.38, and 1.2 to 1.0 Ga correlate across the reconstructed Siberia-Laurentia rift zone. Renewed rifting in the Neoproterozoic and Vendian culminated with seafloor spreading and thermal subsidence of the conjugate rift shoulders. Correlative archeocyathan reefs, endemic olenellid trilobite fauna, and exchange of detritus between the cratons imply that the rift may have remained relatively narrow until the Atdabanian stage. Black sulfidic shales buried the archeocyathan reefs on the rapidly subsiding rift margins during the Botomian Sinsk event.

Keywords: Laurentia, Cordillera, Siberia, Rodinia, plate reconstruction, Proterozoic.

INTRODUCTION

Geologists generally accept that the Cordilleran margin of western Laurentia formed during breakup of a Proterozoic supercontinent (Stewart, 1972; Bond et al., 1984, 1989; Hoffman, 1989, 1991; Dalziel, 1991). Reconstruction of this supercontinent is, however, still debated (Meert, 2002). We proposed that the northeastern margin of the Siberian craton was the conjugate partner of southwestern Laurentia (Sears and Price, 1978, 2000). Other workers have, however, suggested that the Siberian craton was conjugate to the rifted Arctic margin of Laurentia (Poorter, 1981; Condie and Rosen, 1994; Pelechaty, 1996; Frost et al., 1998; Rainbird et al., 1998; Vernikovsky and Vernikovskaya, 2001). Several authors have suggested Australia or Antarctica as the craton conjugate to western Laurentia (Jefferson, 1978; Moores, 1991; Hoffman, 1991; Ross et al., 1992; Young, 1992; Karlstrom et al., 2001); others have suggested that smaller tectonic blocks lay between North America and these continents (Li et al., 1995; Borg and DePaolo, 1994).

Here we present new geological, geophysical, and paleomagnetic data that provide a compelling match in Paleoproterozoic to Early Cambrian geology between the southwestern Laurentian and northeastern Siberian cratons and permit a reasonable Proterozoic connection between the southern Siberian and northern Australian cratons. The resulting Siberia-Laurentia-Australia troika (Fig. 1) is linked by the Grenville collisional belt. We suggest that the troika formed an important component of the Neoproterozoic supercontinent, Rodinia, which aggregated during the Grenville orogeny. Karlstrom et al. (2001) recently correlated the tectonic evolution of the northeastern Australian and southwestern Laurentian cratons. In this paper, we enumerate the geological links supporting our reconstruction of the Laurentian-Siberian-Australian troika and review the geological evolution of the Siberia-Laurentia sector of the troika from the initial stages of its Paleoproterozoic amalgamation to its Early Cambrian breakup and separation.

PALEOMAGNETIC CONSTRAINTS FOR THE TROIKA

Buchan et al. (2000) emphasized the importance of key paleomagnetic poles for appraisal of ancient plate reconstructions. Currently, the only correlative key paleopole data that are available for Proterozoic Laurentia, Siberia, and Australia are at ca. 1070 Ma. Elston et al. (2002) obtained the ca. 1070-Ma Cardenas Lava paleopole for Laurentia. Gallet et al. (2000) obtained the Linok and Malgina paleopoles from the northwestern and southeastern parts of the Siberian craton, respectively. Although these formations are not precisely dated, Gallet et al. (2000) bracket them to ca. 1050–1100 Ma. Wingate et al. (2002) obtained a key 1070 Ma paleopole from the Bangemal basin of western Australia.

The 1070-Ma paleopole data permit a paleocontinental reconstruction involving Siberia, Laurentia, and Australia (Fig. 1). The reconstruction superimposes the paleopoles and juxtaposes correlative geological provinces at appropriate rift margins. If the Linok and Malgina paleopoles are somewhat younger than 1070 Ma, the orientation of the Siberian craton would shift slightly outward with respect to Laurentia, but this could be accommodated by uncertainties in the modification of the continental margins by the rifting process. The position of Australia is slightly modified from the AUSMEX (Australia-Mexico) restoration of Wingate et al. (2002) by rotation along its paleolatitude, to insert the Siberian craton between Laurentia and Australia. The Okhotsk massif (Khudoley et al., 2001) and tectonic slices of Mexico (Sedlock et al., 1993; Keppie and Ortega-Gutiérrez, 1999; Stewart et al.,

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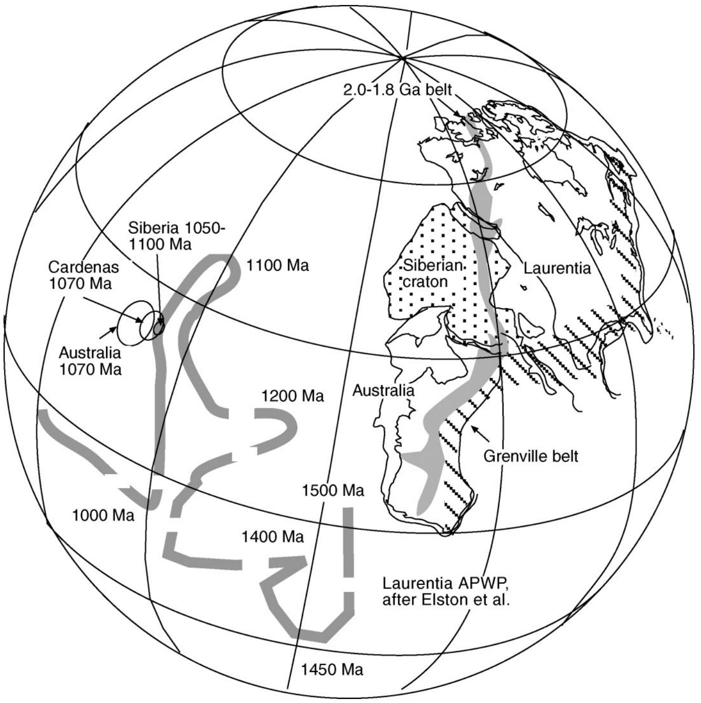


Figure 1. Paleomagnetically permissible Siberia-Laurentia-Australia troika at ~1070 Ma. Geological ties include 2.0–1.8 Ga orogenic belt, 1.5 Ga dike swarm, and 1.3–1.0 Ga Grenville belt. Laurentia held fixed to modern coordinates. Rotation parameters (counterclockwise positive): northwestern Siberia to northwestern Laurentia, 66°N, 315°E, 87.5°; southeastern Siberia to southwestern Laurentia, 74.3°N, 280.9°E, 109.5°; Okhotsk massif to southwestern Laurentia, 73.5°N, 279.2°E, 108.6°; Australia to Laurentia, 50.4°N, 143.6°E, 111.3°. Rotations closed Devonian Vilyuy rift. Laurentian apparent polar wander path from Elston et al. (2002). Siberia poles for 1100–1050 Ma interval from Gallett et al. (2000). Australia 1070 Ma Pole from Wingate et al. (2002). Mexican Grenville reconstructed after Keppie and Ortega-Gutiérrez (1999). We used the GMAP program of Torsvik and Smethurst (2002) for rotations.

2002) may fill the gap between Australia and the southwestern United States. The 1.3–1.0-Ga Grenville orogen, a 2.0–1.8 Ga orogenic belt, and other geologic features discussed below tie the three cratons together. We suggest that Australia drifted away from Laurentia and the Siberian craton to initiate a Neoproterozoic shelf along the southern margin of the Siberian craton (cf. Khain, 1985). That separation preceded Vendian-Early Cambrian Baikalian orogenesis, which involved the southern margin of the Siberian craton (Zonenshain et al., 1990; Pelechaty et al., 1996; Khain et al., 2002). This is consistent with paleomagnetic separation of Australia and Laurentia as of 755 Ma (Wingate and Giddings, 2000).

THE SIBERIA-LAURENTIA FIT

Juxtaposition of the rifted margins of western Laurentia and the northern Siberian craton, in accordance with the paleomagnetic data, forms a tight rabbet joint with a zigzag length greater than 2500 km (Fig. 2). A prominent 200 km offset of the Siberian craton margin at the Laptev Sea (Rosen et al., 1994) fits a 200 km offset of the Laurentian craton margin along the St. Mary-Moyie fault zone, at the Canada-U.S. border (Price and Sears, 2000). The Okhotsk massif of eastern Siberia may have adjoined the southwestern margin of the Laurentian craton along the Texas-Walker lineament. Although the Okhotsk massif has an ambiguous relationship with the Siberian craton, stratigraphic data suggest a Mesoproterozoic linkage (Khain, 1985; Khudoley et al., 2001).

The rifted Siberian and Laurentian cratonic margins are defined by truncations of basement aeromagnetic anomaly patterns (cf. Ross et al., 2000; Smelov et al., 2001), and by large basement ramps beneath foreland thrust and fold belts that mark the edges of the Cordilleran, Verkoyansk, and Taimyr miogeoclines (Price, 1981; Cook and Van der Velden, 1993; Price and Sears, 2000; Kosygin and Parvenof, 1975; Zonenshain et al., 1990; Rosen et al., 1994; Inger et al., 1999; Vernikovsky and Vernikovskaya, 2001). Our geographically tight Siberian-Laurentian connection yields a high-resolution geological match between the two cratons that spans 1.5 b.y., from the Paleoproterozoic to the Early Cambrian. The assembly and amalgamation of the Siberia-Laurentia craton occurred from ca. 2.0 to 1.65 Ga, well before the ca. 1.0 Ga aggregation and consolidation of Rodinia (cf. Hoffman, 1991; Dalziel, 1991). In the following sections, we discuss the geological links in chronological order.

PALEOPROTEROZOIC OROGENIC BELTS

Platformal deposits conceal most of the Siberia-Laurentia basement, but aeromagnetic and gravity anomaly maps and isotopic data from deep boreholes and xenoliths provide the basis for outlining the distribution, origin, and age relationships of distinctive Archean and Paleoproterozoic tectonic domains within the cratonic basement (Hoffman, 1988; Gehrels and Ross, 1998; Ross et al., 2000; Smelov et al., 2001). To reconstruct the Paleoproterozoic orogenic fabric of the two cratons, we have conservatively restored crustal attenuation associated with the opening of the Cordilleran and Taimyr-Verkoyansk miogeoclines. The reconstructed Paleoproterozoic tectonic grain sweeps smoothly across the Siberian connection (Fig. 2A).

The 2.0–1.8 Ga Aldan-Thelon Continental Collisional Belt

A reconstructed 2.0–1.8 Ga continental collisional belt extends some 4500 km, from northwestern Laurentia, across the Siberian connection, and through the eastern Siberian craton. In Siberia, the belt includes the Aldan and Hapshan provinces (Rosen et al., 1994). In Laurentia, it comprises the amalgamated Ksituan, Chinchaga, Buffalo Head, Wabamun, Thorsby, Rimbey, and Talston domains, and the Thelon domain (Ross and Eaton, 2002; Ross et al., 2000; Gehrels and Ross, 1998).

Many workers have observed the close similarities in age, metamorphic grade, structural style, width, and aeromagnetic anomaly signature of these belts (Sears and Price, 1978, 2000; Hoffman, 1991; Frost et al., 1998). On both cratons, the orogenic belts include U-Pb zircon ages of 2.0–1.9 Ga, which date their main periods of plastic deformation and metamorphism (Rosen et al., 1994; Hoffman, 1991; Ross et al., 2000; Griffin et al., 1999;

Frost et al., 1998). On both cratons, the orogenic belts are wedged between rigid to quasi-rigid Archean terranes (Hoffman, 1991; Griffin et al., 1999). On both cratons, east-dipping, 10–30-km-wide granulite-facies shear zones crosscut the orogenic belts. In Laurentia, these include the Great Slave Lake (Hoffman, 1988) and Snowbird shear zones (Ross et al., 2000). In Siberia, they include the Kotuykan and Sayano-Taimyr shear zones (Rosen et al., 1994; Griffin et al., 1999).

Our reconstruction results in consistent orogenic vergence and a coherent pattern of dextral offsets. The Great Slave Lake shear zone merges with the eastern margin of the Siberian craton. The Sayano-Taimyr and Kotuykan shear zones join the Snowbird tectonic zone. The oblique intersections of the orogenic belt and shear zones establish a unique double piercing-point at the Siberian-Laurentian connection.

The 2.0–1.8 Ga continental collisional belt appears to continue across northern Australia as a complex suture zone between a number of small Archean fragments (Fig. 1) (cf. Meyers et al., 1996; Karlstrom et al., 2001).

The 1.9–1.85 Ga Orogenic Belts

The Fort Simpson belt of northwest Laurentia appears to match the Angara belt of Siberia. Although they exhibit different magnetic anomaly values, both are thought to represent 1.9–1.85 Ga magmatic arcs associated with cratonward-dipping subduction zones (Rosen et al., 1994; Ross et al., 2000). The Angara belt may contain reworked Archean crust (Rosen et al., 1994), whereas the Fort Simpson belt is thought to represent juvenile Paleoproterozoic crust (Hoffman, 1988). The belts could have contributed 1.85 Ga detrital zircon to the lower Muskwa assemblage of northeast British Columbia (cf. Ross et al., 2001).

Magnetic anomalies marking the Vulcan belt, along the Hearne-Medicine Hat tectonic boundary in southern Alberta, link with similar anomalies along the Hapshan-Birekte tectonic boundary in Siberia. The Vulcan belt is entirely in the subsurface, and its age and origin are contested (cf. Pilkington et al., 2000). However, the Archean Medicine Hat block trends directly into the Archean Birekte block of Siberia.

The 1.86 Ga Great Falls tectonic zone of Montana (Mueller et al., 2002; Boerner et al., 1998) traces directly into the Paleoproterozoic Aekit terrane of the northeast Siberian craton, which has preliminary K-Ar dates as young as 1.85 Ga (Rosen et al., 1994).

The 1.8–1.7 Ga Orogenic Belts

In our reconstruction, the Archean Wyoming province curves into the Archean Batomga province (Rosen et al., 1994). A Paleoproterozoic craton-marginal quartz-arenite miogeocline follows the southeastern edge of the Wyoming province in the Cheyenne belt of Wyoming and Utah and reappears in the western Mojave province (Condie, 1993). Paleoproterozoic quartz arenite also overlies Archean rock in the southeastern Siberian Ulkan belt (Rosen et al., 1994). A 1.8–1.75 Ga orogenic belt and suture zone along the distal edges of these miogeoclinal remnants appear to pass smoothly from southwest Laurentia to southeast Siberia, although further work is needed to confirm this link.

The Mojave province of Laurentia may correlate with the Okhotsk massif of Siberia. As summarized by Condie (1993), the Mojave province has an enriched Archean cratonic component. Inherited zircons in granitoids reveal xenocrystic material as old as 2832 Ma in Mojave crust (Dubendorfer et al., 2001). Pre-tectonic Mojave intrusions date to 1760–1730 Ma, and syntectonic intrusions to 1710–1700 Ma (Condie, 1993). In southeast Siberia, Archean and 2030–1735 Ma Pb-Pb zircon ages were obtained from Kukhtui granites and granodiorites of the Okhotsk massif (Kuzmin et al., 1995; O. Avchenko, 2002, personal commun.). In our reconstruction, north-trending basement foliations in the Kukhtui uplift parallel those in the Mojave province (O. Avchenko, 2002, personal commun.).

The 1.73–1.70 Ga Ulkan-Colorado Magmatic Arc

Felsic volcanic rocks of the Ulkan fold belt that have been dated at 1.73–1.70 Ga overlie Paleoproterozoic quartz arenite and were folded sometime after 1.70 Ga (Rosen et al., 1994). Our reconstruction places the Ulkan volcanics on trend with correlative felsic igneous rock that has been mapped within the Okhotsk massif and the Mojave Province, Hualapai terrane of Arizona, and Idaho Springs-Black Canyon assemblages of Colorado (Condie, 1993). Cox et al. (2002) interpret the Tonto basin of central Arizona to be a 1.73–1.70 Ga intra-arc basin. Thus, there appears to be a wide, variably deformed, 1.73–1.70 Ga felsic magmatic belt that stitches our reconstruction from Colorado to the southeastern Siberian craton. Detrital zircons separated from the Uchur Group quartzite of southeast Siberia (Khudoley et al., 2001), and detrital monazite from the Ortega Quartzite of New Mexico (Kopera et al., 2002), may reflect sources from this Ulkan-Colorado magmatic belt. The 1.73–1.70-Ma Ulkan-Colorado felsic magmatic belt may have extended into the Murphy inlier of the Mount Isa belt, northern Australia, which contains 1.73 Ga felsic rocks (Southgate et al., 2000). At ~1.7–1.65 Ga, during accretion of the Mazatzal province (Van Schmus and Bickford, 1993; Karlstrom and Bowring, 1993; Karlstrom et al., 2001), a single orogenic belt may have extended from Colorado to Siberia and Australia.

MESOPROTEROZOIC BASINS AND IGNEOUS PROVINCES

A number of distinctive Mesoproterozoic geologic provinces formed after Paleoproterozoic aggregation and consolidation of the Siberian and Laurentian cratons. These provide additional piercing points that test our reconstruction.

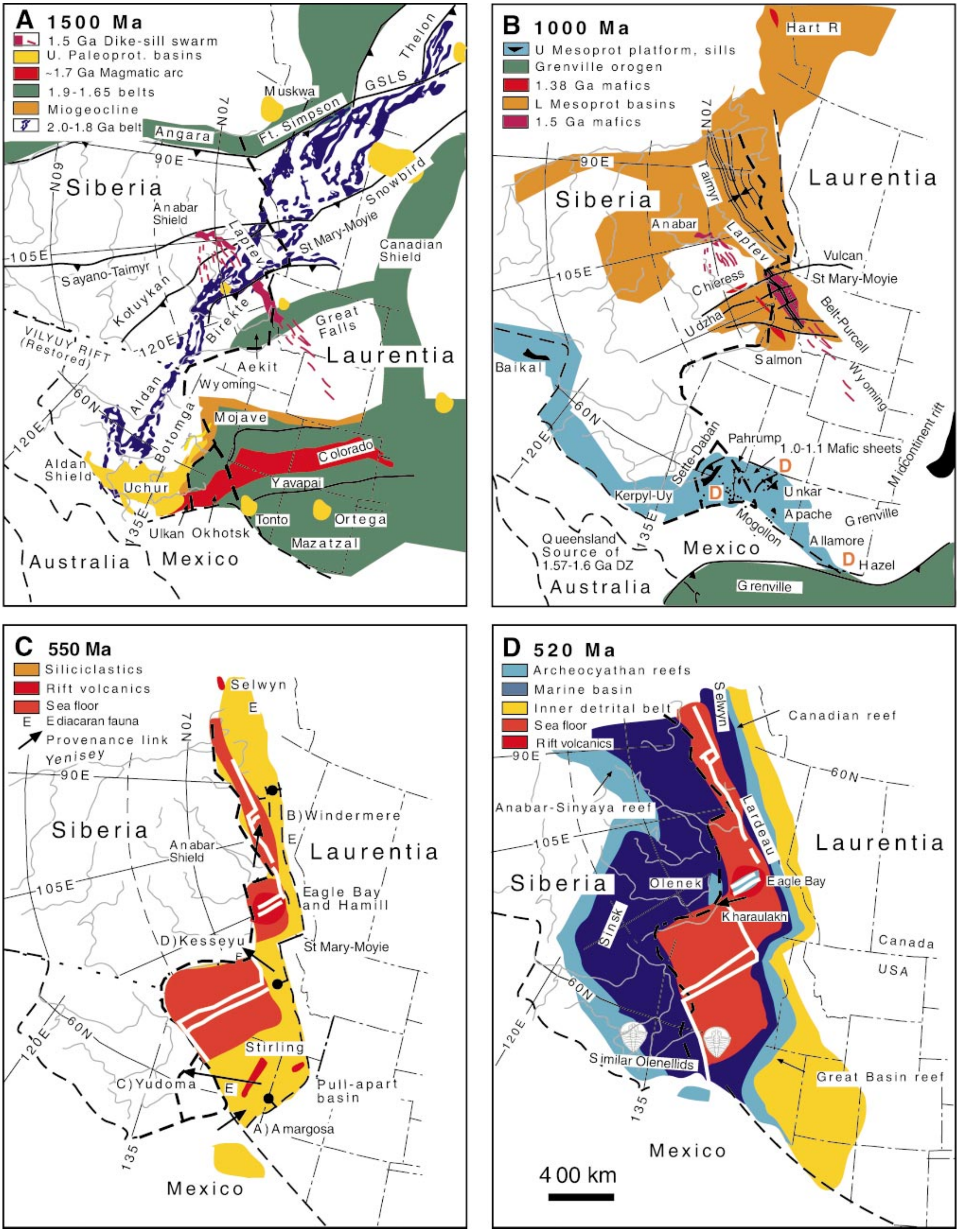
Early Mesoproterozoic Anabar-Wyoming Dike-Sill Swarms

The Siberian and Laurentian cratons were crosscut at ca. 1500 Ma by mafic dike-sill swarms. These form an aligned belt, more than 1000-km long, that effectively cross-stitches our Siberia-Laurentia connection from the southern Wyoming province to the central Anabar shield (Fig. 2, A and B). K-Ar dates of ca. 1450 Ma are reported from dikes on both cratons (Okrugin et al., 1990; Harlan et al., 1997). A dike in central Wyoming was U-Pb dated at 1469 Ma (Chamberlain et al., 2000). The Kuonamka mafic dike swarm in the Anabar shield yielded a provisional U-Pb baddeleyite emplacement age of 1503 ± 5 Ma (Ernst et al., 2000).

Widespread mafic sills on the west flank of the Anabar shield yield K-Ar ages as old as 1453 Ma (Okrugin et al., 1990). On Laurentia, voluminous Belt-Purcell sills and flows have been U-Pb dated to 1468, 1456, and 1443 Ma (Sears et al., 1998; Anderson and Davis, 1995; Evans et al., 2000). There is an indication of 1501 Ma sills in the subsurface of the Belt-Purcell basin (Anderson and Parrish, 2000). Rifting that initiated the Belt-Purcell basin and its associated sills and dikes appears to have begun at 1510–1485 Ma (Lydon, 2000). Precise U-Pb data are needed from the west Anabar sills to tighten this correlation.

Mesoproterozoic Belt-Purcell and Udzha-Taimyr Rift Basins

The Belt-Purcell Supergroup of the Cordilleran fold-thrust belt palinspastically restores


A 1500 Ma
1.5 Ga Dike-sill swarm
U. Paleoprot. basins
~1.7 Ga Magmatic arc
1.9-1.65 belts
Miogeocline
2.0-1.8 Ga belt
Angara
Ft. Simpson
Muskwa
GSLS
Thelon
70N
90E
60N
Siberia
Anabar Shield
Laptev
Snowbird
St Mary-Moyie
Canadian Shield
105E
Sayano-Taimyr
Kotuykan
Birekte
Great Falls
VILYUY RIFT (Restored)
120E
Aekit
Laurentia
Wyoming
Aldan
Botomga
Mojave
Colorado
Aldan Shield
Uchur
Yavapai
Tonto
Ortega
135E
Ulkan
Okhotsk
Mazatzal
Australia
Mexico
B 1000 Ma
U Mesoprot platform, sills
Grenville orogen
1.38 Ga mafics
L Mesoprot basins
1.5 Ga mafics
Hart R
70N
90E
Taimyr
Laurentia
Siberia
Anabar
Laptev
Vulcan
105E
Chieress
St Mary-Moyie
Belt-Purcell
Udzha
Salmon
Baikal
Wyoming
60N
Pahrump
Sette-Daban
1.0-1.1 Mafic sheets
Midcontinent rift
120E
D
Kerpyl-Uy
D
Unkar
Apache
Grenville
135E
Queensland Source of 1.57-1.6 Ga DZ
Mexico
Mogollon
Allamore
D
Hazel
Australia
Grenville
C 550 Ma
Siliciclastics
Rift volcanics
Sea floor
E Ediacaran fauna
Provenance link
Yenisey
Selwyn
E
70N
90E
B) Windermere
E
Siberia
Anabar Shield
Laurentia
105E
Eagle Bay and Hamill
D) Kesseyu
E
St Mary-Moyie
60N
120E
Stirling
C) Yudoma
E
Pull-apart basin
A) Amargosa
135
Mexico
D 520 Ma
Archeocyathan reefs
Marine basin
Inner detrital belt
Sea floor
Rift volcanics
Selwyn
Canadian reef
90E
60N
Anabar-Sinyaya reef
Lardeau
105E
Laurentia
Siberia
Olenek
Eagle Bay
Kharaulakh
Sinsk
Canada
USA
60N
120E
Similar Olenellids
Great Basin reef
135
Mexico
400 km

into a northwest-trending rift basin (Price and Sears, 2000) that aligns with the Siberian Taimyr trough in our reconstruction (Fig. 2B). A thick succession of Mesoproterozoic sedimentary strata and sills that appears to be correlative with the Belt-Purcell Supergroup emerges along the southern margin of the Taimyr trough on the flank of the Anabar massif (cf. Okrugin et al., 1990). Mesoproterozoic strata along the northern flank of the Taimyr trough have been displaced horizontally within the Mesozoic Taimyr fold-thrust belt (Zonenshain et al., 1990; Inger et al., 1999; Vernikovsky and Vernikovskaya, 2001). We have conservatively restored them in Figure 2B. Mesoproterozoic platform sediments flank the distal ends of the reconstructed Belt-Purcell-Taimyr rift on both the Siberian and Laurentian sides (Fig. 2B), in a pattern suggestive of a rift valley intersecting a continental margin. Isopachs of the palinspastically restored Belt-Purcell Supergroup are abruptly truncated at the Laurentian margin in northeastern Washington (Harrison, 1972; Cressman, 1989; Price and Sears, 2000). In our restoration, they trend toward isopachs of the Taimyr trough that are truncated at the Laptev Sea (cf. Kosygin and Parvenof 1975; Rosen et al., 1994).

Several syndepositional, northeast-trending transform faults segmented the rift axis of the Belt-Purcell basin (Höy et al., 2000). Our reconstruction aligns the St. Mary and Moyie transform faults with the Siberian Udzha trough (Fig. 2B). The Udzha trough is a narrow rift, 400 km long, reportedly filled with more than 9 km of Mesoproterozoic sediments (Zonenshain et al., 1990), although little is exposed at the surface. The reconstructed St. Mary-Moyie-Udzha fault zone appears to have been a major transform fault system that formed by reactivation of segments of the Vulcan structure of western Laurentia (cf. Price and Sears, 2000) and Hapshan belt of Siberia. The world-class Sullivan sedimentary exhalative base-metal sulphide deposit formed along that transform fault system (Höy et al., 2000). The transform fault zone, which was reactivated during both Neoproterozoic (Lis and Price, 1976) and Vendian to Early Cambrian rifting (Warren, 1997; Price and Sears, 2000), ultimately evolved into the prominent cognate offsets of the rift margins shown in Figure 2B.

Price (1964) interpreted the large-volume, dominantly fine grained, turbiditic, lower Belt-Purcell Supergroup as the deposits of a large river that drained a low-relief, continental-scale basin. Using paleocurrent measurements, Cressman (1989) located the mouth of this Belt-Purcell River at a distinct point on the southwestern side of the basin, near Spokane, Washington. Cressman (1989) interpreted the Siberian craton as the source of the lower Belt-Purcell sediments. On our reconstruction, the sediment-input point coincides with the truncated end of the Udzha trough. We suggest that the Udzha trough captured a large basin that included parts of the Siberian craton and northern Australia. Rapid erosion of a fine-grained pediment veneer within this basin would explain the rapid deposition of the fine-grained lower Belt-Purcell Supergroup (cf. Lydon, 2000).

Frost and Winston (1987) found that most of the fine-grained sediments of the Belt-Purcell Supergroup were derived from source terranes with 2.1–1.9 Ga crustal-residence ages. This may indicate sources in the Aldan-Hapshan orogenic belt. Ross and Villeneuve (1999) summarized extensive detrital zircon data from the Belt-Purcell Supergroup. The Aldridge Formation, which comprises the lower turbiditic member of the Belt-Purcell Supergroup in Canada, is characterized by detrital zircons that could have been derived from a broad drainage basin that was underlain by the Archean rocks of the Batomga and Wyoming Provinces and framed by remnants of the Aldan-Hapshan belt and the Ulkan-Colorado magmatic belt. Younger Belt-Purcell rocks include zircons having the unusual age range of 1510–1610 Ma (Ross and Villeneuve, 1999). The Kerpyl Group of southeastern Siberia has a detrital zircon age spectrum similar to the upper Belt-Purcell Supergroup, including a 1510–1610 Ma peak (Khudoley et al., 2001). These require source rocks that are rare in Laurentia and unknown in Siberia, but common in Queensland, Australia (cf. Blewett et al., 1998). The Laurentia-Siberia-Australia troika of Figure 1 would provide appropriate source rocks in northern Australia (cf. Blewett et al., 1998), to supply both Siberia and Laurentia with such detrital zircons. Note that, although the Gawler craton also has appropriately-aged source rocks (cf. Ross et al., 1991, 1992), it apparently did not amalgamate with northern Australia until the Grenville orogeny (cf. Wingate et al., 2002), and so it is an unlikely source in our reconstruction.

Figure 2. Correlations across the Siberia-western Laurentia connection at four separate times. (A) Early Mesoproterozoic (ca. 1500 Ma) Siberia-Laurentia reconstruction, following amalgamation of basement terranes and prior to opening of early Mesoproterozoic rift basins. Edge of Siberian craton taken at Verkoyansk and Taimyr thrust ramps (after Rosen et al., 1994; Kosygin and Parvenof, 1975). Edge of Laurentian craton approximates 0.704 initial strontium ratio isopleth (Armstrong, 1988; Levy and Christie Blick, 1993), and craton margin ramp of Cook and Van der Velden (1993) and Price and Sears (2000). Note matching offsets of margins at Laptev Sea and USA-Canada border. Northern Alberta province includes Ksituan, Chinchaga, Buffalo Head, Wabamun, Thorsby, and Rimbey zones of Gehrels and Ross (1998). GSLSZ—Great Slave Lake Shear Zone. Siberian geology mostly after Rosen et al. (1994) and Smelov et al. (2001). Laurentian geology mostly after Hoffman (1988) and Condie (1993). Magnetic anomalies after Litvinova (1996) and Ross et al. (2000). (B) Late Mesoproterozoic (ca. 1000 Ma) Siberia-Laurentia restoration. Cratons separated to accommodate Belt-Purcell-Taimyr rift. Taimyr trough axis (after Rosen et al., 1994) aligns with Belt-Purcell basin axis (after Höy et al., 2000; Price and Sears, 2000). St. Mary-Moyie fault zone, active during Belt-Purcell deposition, aligns with Udzha trough (Rosen et al., 1994; Zonenshain et al., 1990), which coincides with sediment input point for lower Belt-Purcell Supergroup (Cressman, 1989). St. Mary-Moyie fault zone eventually separated Taimyr and Belt-Purcell segments of basin. D—Grenville detritus. (C) Vendian Siberia-Laurentia restoration (ca. 550 Ma). Southeastern Siberia may have shed clastic sediments into Amargosa basin (Site A). Carbonate shelf on northern Siberia may have shed shallow carbonate clasts into Windermere turbidite basin (Site B). Laurentian siliclastic wedge may have periodically spilled detritus onto Siberian shelf (Sites C, Yudoma Group, and D, Kesseyu Formation). Vendian-Early Cambrian rift volcanics found along both sides. Suggested rift-transform configuration permits sediment linkage. (D) Early Cambrian (ca. 520 Ma) Siberia-Laurentia restoration. Eagle Bay volcanics at Early Cambrian spreading ridge may have spilled onto Kharaulakh Mountains near Olenek promontory. Archeocyathan reefs fringe both cratons. The Laurentian reef may have crossed to the Olenek promontory at Eagle Bay spreading ridge. Mostly after Fritz et al. (1991), Riding and Zhuravlev (1995), Pope and Sears (1997), and Stewart (1970).

The 1.38–1.37 Ga Chieress-Salmon Igneous Province

Both the Udzha and Belt-Purcell basins were intruded by mafic magma at 1.38–1.37 Ga. Globally, this represents a relatively rare date for a mafic event (Ernst et al., 2000). The Chieress dike swarm intruded basement rocks and overlying Mesoproterozoic strata on the flank of the Udzha trough. It has provided a precise U-Pb baddeleyite emplacement age of 1384 ± 2 Ma (Ernst et al., 2000). Our reconstruction plots the Chieress site within 200 km of the 1.37-Ga intrusives in the southern and western parts of the Belt-Purcell basin (Doughty and Chamberlain, 1996; Evans et al., 2000). The distribution of the mafic province suggests renewed rifting and magmatism at the junction of the Udzha trough and Belt-Purcell basin. The correlative Ogilvie sills in Yukon Territory (Abbott, 1997) may indicate a continuation of the 1.38–1.37 rift event along the Belt-Purcell-Taimyr basin.

The 1260 Ma Baikal-Allamore Sedimentary Platform

A broad belt extending across southwestern Laurentia, from western Texas to Death Valley, contains remnants of platform sediments that are tightly correlated to 1250–1260 Ma by U-Pb dating of interlayered ash beds (Fig. 2B). These include the Allamore, Apache, and Unkar Groups, and, probably, the basal Pahrump Group (Van Schmus and Bickford, 1993). These strata overlie Paleoproterozoic basement with profound angular unconformity. They may be equivalent to similar platform sediments of the Aimchan and Kerpyl Groups of southeastern Siberia that similarly overlie a profound unconformity and predate ca. 1000 Ma sills (cf. Khudoley et al., 2001). Remnants of this platform may continue across the southern margin of the Siberian craton to Lake Baikal (Khain, 1985), perhaps linked with the initiation of rifting between Australia and Siberia.

Detrital Zircon Provinces

There is correlation of detrital zircon age spectra between sites in southeastern Siberia and southwestern Laurentia that are situated adjacent to one another in our reconstruction. Stewart et al. (2001) and Gehrels (2000) tabulated detrital zircon age spectra for Mesoproterozoic-to-Cambrian–age arenites of the southwestern United States and northwestern Mexico. These can be compared with more preliminary data from correlative strata in southeastern Siberia reported by Khudoley et al. (2001). The Mesoproterozoic Kerpyl Group of Siberia has a detrital zircon peak from 1900 to 2000 Ma, which overlaps the assembly age of the Siberian craton, but 13 of 33 grains range from 1300 to 1700 Ma and are younger than rocks reported from the Siberian craton. The source of these zircons may have been in Laurentia (Khudoley et al., 2001). The exotic part of the Kerpyl Group age histogram resembles the age spectra of the Dripping Spring Quartzite or El Alamo Formation of southwestern Laurentia shown by Stewart et al. (2001). Both require some sources outboard of either Siberia or Laurentia. The Uy Group detrital zircon age histogram of Siberia (Khudoley et al., 2001) resembles the Neoproterozoic Sonora reference age spectrum of Gehrels (2000).

The 1.0–1.1 Ga Sette-Daban-Mogollon Mafic-Sheet Province

Howard (1991) mapped a large belt in southwestern Laurentia that is characterized by ca. 1.1–1.0 Ga diabase sheets. These intrude the basement and platform cover. They may comprise a branch from the Laurentian Mid-continent rift (Adams and Keller, 1994). The southern Death Valley region contains voluminous diabase sills, individually as thick as 365 m (Howard, 1991). One sill was U-Pb dated by Heaman and Grotzinger (1992) to 1080 Ma. In our reconstruction (Fig. 2B), the mafic sheets of central Arizona and eastern California and Nevada are closely adjacent to voluminous mafic sills having an aggregate thickness of 1 km, in the Lakhanda and Uy Groups of southeastern Siberia; these recently were U-Pb dated to 1.0–0.9 Ga (Rainbird et al., 1998). Gabbro and ophiolite that have been U-Pb dated to 1010–1190 Ma are reported from the southern margin of the Siberian craton (Khain et al., 2002).

Grenville Foreland Basin

Grenville foreland basin deposits of Laurentia are locally preserved from west Texas to the Grand Canyon. The Hazel Formation of west Texas is a red-bed conglomerate comprising proximal fan deposits with boulders of 1.1 Ga gneiss that were derived from the adjacent Grenville Province (Soegaard and Callahan, 1994). Deposition probably continued to 1080 Ma, after which the Hazel Formation was involved in foreland thrusting (Soegaard and Callahan, 1994; Bickford et al., 2000). Cannon (1994) showed that the Midcontinent rift experienced Grenville foreland compressional deformation from 1080 to 1060 Ma. In the Grand Canyon, the upper Unkar Group yielded detrital zircons with fission track ages of 1.1 Ga (Naeser et al., 1989). The Unkar Group underwent northwest-verging reverse faulting and folding before and after intrusion of ca. 1.1-Ga diabase sills (Huntoon and Sears, 1975).

The Upper Uy Group (Mayamkan Formation) of Siberia is an immature red-bed sequence with abundant detrital zircons that are correlative with the ca. 1.0 Ga Grenville Province and ca. 1.4 Ga anorogenic magmatic rocks of southwestern Laurentia (Rainbird et al., 1998). The Uy Group underwent west-verging reverse faulting after intrusion by diabase sills and prior to deposition of the Vendian Yudoma Group (Khudoley and Guriev, 2003). In our reconstruction, the *en echelon* reverse faults of the Uy and Unkar Groups represent compressional deformation within the broad Grenville foreland basin.

Grenville-age deformation occurs across Mexico (Keppie and Ortega-Gutiérrez, 1999) and central Australia (Wingate et al., 2002). We reconstruct a continuous Grenville orogenic belt that extends across the Laurentia-Siberia-Australia troika; it is compatible with the 1070 Ma paleomagnetic data that were discussed above (Fig. 1). The Grenville-age collisions presumably occurred during the formation of the larger Rodinia supercontinent (Hoffman, 1991; Karlstrom et al., 2001).

NEOPROTEROZOIC-EARLIEST CAMBRIAN RIFTING

We suggest that Neoproterozoic to earliest Cambrian continental rifting eventually broke apart the Siberia-Laurentia connection. Regional unconformities record episodes of Neoproterozoic uplift and erosion of the eastern margin of the Siberian craton and the western margin of Laurentia (Pelechaty et al., 1996; Bartley et al., 1998; Khudoley et al., 2001; Ross, 1991; Karlstrom et al., 2000; Timmons et al., 2001). In Laurentia, several episodes of rifting are documented between 780 and 570 Ma (Colpron et al., 2002; Lund et al., 2003). Diamictites and rift volcanics had continuity along the Laurentian side of the rift from northern Canada to Death Valley by 685 Ma (Ross et al., 1995; Prave, 1999; Lund et al., 2003). Ediacaran faunas occur at shelf-edge localities along both the Siberian and Laurentian margins (Fig. 2C) (Fedonkin, 1992). The rift zone followed Mesoproterozoic structural trends in the north, but a new pull-apart basin appears to have opened in the region of the Great Basin. By late Vendian time, the subsiding cratons behaved as distinct tectonic blocks, with the eastern Siberian craton largely covered by a carbonate platform and western Laurentia covered by thick siliciclastics. Sediment, however, appears to have episodically spilled across the rift zone in either direction, suggesting that the two cratons remained in proximity until the Early Cambrian, with the intervening rift basin rapidly filling with sediment. An Atdabanian archeocyathan reef may provide the youngest piercing-point link between the cratons. Botomian black shale deposits that transgressively overlap the archeocyathan reefs on both margins may record thermal subsidence of the conjugate margins upon establishment of full-scale seafloor spreading between the two separating continental cratons. We model the early spreading system as a series of rifts and transforms (Fig. 2, C and D).

Laurentia

In southwestern Canada, east-tilted half-grabens were filled with thick rift-facies volcanics and immature clastic sediments of the lower Windermere Supergroup (Warren, 1997). Uplift of Laurentian basement and parts of the Belt-Purcell Supergroup shed debris into the Windermere basin along the St. Mary-Moyie transverse fault zone (Lis and Price, 1976; Price and Sears, 2000). Windermere feldspathic grits contain distinctive suites of detrital zircons indicative of a provenance in uplifted basement rocks of southwestern Canada (Ross and Bowring, 1990), or possibly the correlative Anabar shield, which was partly exposed at the time. The grit forms an extensive, deep-water turbidite fan in which flow was mainly to the northwest (Ross et al., 1995). Several workers have suggested that the Windermere rifting records continental separation (Ross et al., 1995; Dalziel, 1991; Young, 1992; Karlstrom et al., 2001). However, Colpron et al. (2002) suggested that the Windermere basin was an intracratonic rift that opened northwestward into a passive continental margin in the Yukon, where Dalrymple and Narbonne (1996) and MacNaughton et al. (2000) described a Neoproterozoic carbonate platform and related continental-slope contourites.

Vendian-age, allodapic carbonate is interbedded with deep-water, turbiditic, feldspathic grit in the upper Windermere Supergroup (Ross et al., 1995). Clasts in the carbonates include shallow-water grapestones, oncoids, and multicoated grains. In our reconstruction, the Vendian carbonate shoals of Siberia provide a convenient source, and the Siberian ramp facies provides an appropriate transport zone for the allodapic carbonate detritus (cf. Pelechaty et al., 1996). This possible linkage between the cratons is a candidate for further sedimentological research.

The 570 Ma rifting event is well documented north of the St. Mary-Moyie fault zone. Colpron et al. (2002) and Lund et al. (2003) interpret this rifting event to have led to the opening of an ocean basin and separation of the conjugate cratons. Clastic sediments of the late Vendian to Early Cambrian Hamill and Gog Groups accumulated rapidly in half-graben basins bounded by growth faults (Devlin and Bond, 1986; Warren, 1997; Kubli and Simony, 1992; Lickorish and Simony, 1995). These half-grabens were superimposed upon and shared the tilt sense of the set of half-grabens in which the Windermere Supergroup had accumulated (Warren, 1997). The eastern basins have fluvial and marginal marine clastic facies, while the western basins are transitional to open-marine and contain thick rift-volcanic sequences. The basins have internal unconformities, and sediment reaches a maximum thickness of 2 km along some graben axes (Fritz et al., 1991). Detrital zircon geochronology indicates provenance in adjacent regions of the Laurentian rift shoulder in southwestern Alberta (Gehrels and Ross, 1998).

Synrift volcanics of the middle Hamill Group have the geochemical signature of a continental rift and have provided a concordant U-Pb zircon age of ca. 570 Ma (Colpron et al., 2002). Further evidence of Vendian magmatic activity in the Canadian segment of the rift system comes from ~140 km to the southwest, near Vernon, British Columbia, where a granite-cobble conglomerate has provided zircons that are U-Pb dated at 555 Ma (Erdmer et al., 2001). About 150 km northwest of Vernon, the Eagle Bay assemblage contains ~2 km of bimodal volcanics and volcaniclastics that represent a distal continuation of the Hamill Group volcanics (Hughes et al., 2000). The Eagle Bay volcanics are intercalated with Vendian siliclastics and minor carbonate below and thick archeocyathan limestone above (Schiarizza, 1986; Hughes et al., 2000). Eagle Bay geochemistry indicates a transition from continental rift affinity in the older parts, associated with the siliclastics, to mid-oceanic–ridge basalt (MORB) affinity in the younger parts, associated with the archeocyathan limestone (Hughes et al., 2000). In our paleogeographic reconstruction (Fig. 2C), the Eagle Bay assemblage lies outboard of the Laurentian $^{87}Sr/^{86}Sr = 0.704$ isopleth (cf. Price and Sears, 2000; Armstrong, 1988). Hughes et al. (2000) suggested that the Eagle Bay volcanics represent an anomalously large volcanic accumulation, perhaps a hotspot, at the very edge of Laurentia that records the onset of seafloor spreading.

The uplifted corners of some of the Canadian tilt-blocks stood above the adjacent depositional basins until the Atdabanian stage, when they subsided and were buried by post-rift quartz arenite and archeocyathan limestone of the *Nevadella* and *Bonnia-Ollenellus* zones (Kubli and Simony, 1992; Warren, 1997; Fritz et al., 1991). In the Dogtooth Mountains of British Columbia, Fish Lake volcanic breccias, tuffs, and basalt flows overlie an erosional unconformity that cuts into *Scolithus*-burrowed sandstones of the upper Hamill Group and underlie Atdabanian archeocyathan limestone and trilobitic bioclastic limestone of the Donald Formation (Devlin, 1989; Kubli and Simony, 1992; Lickorish and Simony, 1995). Basaltic breccias are also found in the Selwyn basin, Yukon, associated with archeocyathans (Fritz et al., 1991).

In California, the Amargosa basin occupied an east-trending rift (Link et al., 1993) near our proposed Siberia-Laurentia connection. Southerly-derived feldspathic sediment in the Kingston Peak Formation of the Amargosa basin (Prave, 1999) could have originated in southeastern Siberia (site A, Fig. 2C).

The Great Basin region of Laurentia contains a very thick (up to 3–4 km) Vendian to Early Cambrian siliciclastic wedge (Stewart, 1970, 1972). Detrital zircon provenance, paleocurrent, and Nd-isotope data indicate that the siliciclastic sediment was derived from Laurentian basement provinces to the east and spread by fluvial processes across a broad, rapidly subsiding basin (Stewart et al., 2001; Farmer and Ball, 1997).

Siberia

Thin sandstone layers are interbedded with Vendian to Early Cambrian shelf carbonates along the southeastern and northeastern Siberian platform; these sandstones appear to have been derived from outboard of the Siberian craton, which was largely covered by carbonate at the time (Khudoley et al., 2001; Pelachaty et al., 1996; Bowring et al., 1993). We suggest that the Vendian to Early Cambrian siliciclastics of southwestern Laurentia episodically spilled onto the adjacent Siberian carbonate shelf. The rift-transform pattern of Figure 2C provides sediment linkage across some segments of the plate boundary.

Specifically, in southeastern Siberia (site C, Fig. 2C), sands interlayered with Yudoma Group dolomite contain detrital zircon grains dated at 2195–2018 Ma, which were derived from east of the Siberian craton (Khudoley et al., 2001). That age range correlates well with potential source rocks in the Mojave Province (Dubendorfer et al., 2001; Karlstrom and Bowring, 1993). Furthermore, the Vendian sediment dispersal pattern documented for the southwestern Laurentia siliciclastic wedge had the appropriate sense to transport grains from the Mojave Province to the Yudoma Group.

In another example, four detrital zircon grains from the Early Cambrian Kesseyu Formation on the Olenek promontory (site D, Fig. 2C) gave Pb-Pb ages of 643, 1832, 2290, and 2387 Ma (Bowring et al., 1993). In our paleogeographic reconstruction, the Olenek site plots near provinces of Laurentia that could have supplied the grains. The Early Cambrian Osgood Mountains Quartzite of Nevada, which plots near the Olenek promontory in our reconstruction, also has Paleoproterozoic detrital zircon (Gehrels, 2000). Detrital zircon from the Grand Forks complex of southeastern British Columbia ranged from 570 to 674 Ma, with one 644 Ma grain (Ross et al., 1991). Paleocurrents shown by Stewart et al. (2001) could link the Kesseyu and Grand Forks sites on our restoration.

The northern Siberian craton margin experienced Vendian-Early Cambrian rifting and igneous activity (Pelechaty, 1996). The Olenek promontory is a fault-bounded rhomb of the Siberian platform, riven with Vendian-Early Paleozoic northwest-trending normal faults. Tilting of the Olenek block began by ca. 555 Ma and continued into the Early Cambrian (Pelechaty, 1996). Nemakit-Daldyn strata (lowermost Cambrian) unconformably onlap the southwest-tilted Vendian Khorbosuonka Group and thicken into a southwest-facing basin (Pelechaty, 1996). Post-rift sediments begin at 530 Ma. Bowring et al. (1993) U-Pb dated zircons separated from an Early Cambrian volcanic breccia in the Olenek block at 543 Ma and zircons from volcanic cobbles of a fluvial conglomerate in the neighboring Kharaulakh Mountains at 534 Ma. The conglomerate and associated pillow basalts underlie Tommotian strata. The volcanic cobbles were likely derived from outboard of the Siberian craton (Bowring et al., 1993), perhaps Laurentia. In Figures 2C and D, the Olenek promontory drifts past the spreading ridge during this time interval and could receive sediments from the Eagle Bay volcanics.

Pillow basalt boulders of possible Early Cambrian age occur with archeocyathans in Scott Canyon, Nevada, at the edge of Laurentia (Stewart and Suczek, 1977). Stewart (1974) reported basalt interlayered with the Vendian-earliest Cambrian Stirling Quartzite of Nevada, which underlies the Tommotian-age Wood Canyon Formation. The volcanics are as much as 30-m thick and occur along a strike length of >200 km. They fill broad channels, record detrital reworking at the top, and are interlayered with fluvial conglomerate.

The above correlations suggest some sedimentologic connection between Siberia and Laurentia as late as Early Cambrian. Vernikovsky and Vernikovskaya (2001) interpreted geochronologic data from the Taimyr belt to indicate that the northern margin of the Siberian craton was convergent by Neoproterozoic. However, their data came from suture zones within the accretionary margin of the Taimyr orogen and may not relate to the Siberian craton margin, which first began collisional orogenesis in the late Paleozoic (Inger et al., 1999).

Early Cambrian Olenellids

A major compilation of the distribution of Olenellid trilobites by Palmer and Repina (1993) shows that four of the earliest genera occur in Atdabanian deposits that plot directly adjacent to one another on our paleogeographic reconstruction (Fig. 2D). Primitive Nevadiid trilobites are shared by the northeastern Siberian craton and the Laurentian Cordillera. Primitive Ollenellid genera were notoriously endemic and short-lived (Palmer and Repina, 1993). The Cambrian time-scale revision condenses the span of individual Atdabanian trilobite zones to as few as 750,000 yr (Bowring et al., 1993).

Because of their diminutive ranges in time and space, correlations of Siberia-Laurentia Ollenellids at the genus level may prove to be exceptionally significant for paleogeographic reconstructions. The Olenellid correlations suggest proximity of the conjugate margins during Atdabanian time, ca. 530 Ma, but Siberia-Laurentia trilobite genera appear to have abruptly diverged in Botomian time (Briggs and Fortey, 1992).

Early Cambrian Archeocyathan Reefs

Archeocyathan reefs associated with red limestone and shale fringed both margins (Fritz et al., 1991; Rozanov and Zhuravlev, 1992) and may provide the youngest piercing points for the Siberian connection (Fig. 2D).

The 1500-km-long Siberian Anabar-Sinyaya reef snakes across the Siberian craton in concert with the rift zone. This reef, which includes the global origination point for archeocyathans in the early Tommotian stage, continued to grow through the Atdabanian (Riding and Zhuravlev, 1995, Rowland et al., 1998). A second occurrence of archeocyathans, in the northeastern Anabar uplift and Olenek uplift, is isolated from the Anabar-Sinyaya reef by a wide belt of shaley, open marine facies (Riding and Zhuravlev, 1995; Zhuravlev, 1996).

The Laurentian archeocyathan reef is Atdabanian-Botomian in age and lies along the distal edge of the miogeocline above thick siliciclastics (Fritz et al., 1991; Pope and Sears, 1997). When archeocyathan genera dispersed from Siberia to North America in late Atdabanian, their distribution was restricted to low-latitude shelves with low siliciclastic influx (Debrenne, 1992). Archeocyathan colonization of the west Laurentian margin thus awaited the eastward shift of siliciclastic deposition during the Sauk transgression.

On our restoration, the Laurentian reef crosses to Siberia at the Olenek promontory (Fig. 2D), where the oldest archeocyathans also are Atdabanian age (Kaufman et al., 1996). The spreading ridge, possibly represented by the Eagle Bay volcanics, may have bridged the space between the continents. The Eagle Bay volcanics have a thick archeocyathan limestone that may represent a fringing reef (Schiarizza, 1986; Hughes et al., 2000).

Sinsk Event

The Sinsk event extinguished most of the archeocyathan reef consortium in mid-Botomian time (Zhuravlev, 1996). The event is recorded by condensed, eutrophic, varved, bituminous black shale with primary pyrite framboids in the Sinsk and Kuonamka formations, which cover 750,000 km^2 of the northeast Siberian craton and bury the archeocyathan reefs (Zhuravlev, 1996; Brasier and Sukhov, 1998). The Sinsk event was due to rapid sea-level rise and resulting starved-basin conditions (Brasier and Sukhov, 1998; Brasier et al., 1994). In southeastern British Columbia, jet-black, pyritic shales of the Index Formation abruptly overlie the archeocyathan Badshot limestone (Sears and Price, 1977). In the Yukon, black shales of the Botomian Road River Group overlie Sekwi Formation, which contains Atdabanian archeocyathans (Fritz et al., 1991). In the Great Basin, Cambrian Grand Cycle transgression deposited basinal shale on Poleta Formation archeocyathan limestone (Pope and Sears, 1997). Stratiform sulfide ore deposits occur with the black shales along both margins. The burial of the archeocyathan reefs by black shale may record rapid thermal subsidence of the Siberian and Laurentian continental margins as well as eustatic sea-level rise, possible synergistic results of sea-floor spreading. Bond and Kominz (1984) and Levy and Christie-Blick (1991) showed that the subsidence of the Cordilleran miogeocline began in late Vendian to Early Cambrian. Khudoley and Serkina (2002) reported a similar finding for the Verkoyansk miogeocline.

CONCLUSION

We conclude that the Siberia-western Laurentia connection provides a tight geographical fit with high geological resolution. Furthermore, the reconstruction is compatible with available key paleomagnetic data and permits a Siberia-Laurentia-Australia continental troika at ca. 1070 Ma. Our proposed paleogeographic reconstruction is a reasonable template for interpreting the geological history of the Siberian and Laurentian cratons from 2000 to 520 Ma. It provides numerous opportunities for further international collaborative research into paleogeographic reconstructions, the nature of continental rifting and sedimentation, and the radiation of Vendian and early Cambrian metazoa.

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