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Linking the Mesoproterozoic Belt-Purcell and Udzha basins across the west Laurentia–Siberia connection

James W. Sears[a,*], Raymond A. Price[b], Andrei K. Khudoley[c]

[a] University of Montana, Missoula, MT 59812, USA
[b] Queen's University, Kingston, Ont., Canada K7L3N6
[c] St. Petersburg State University, St. Petersburg, Russia

Abstract

Paleogeographic reconstruction of the northern Siberian craton against southwestern Laurentia, in accordance with paleomagnetic data, basement piercing points, and the best fit of the rift margins, aligns Mesoproterozoic dike and sill swarms in northeast Siberia with correlative ones in Montana and Wyoming. It also juxtaposes the Mesoproterozoic Belt-Purcell basin of west Laurentia against the Mesoproterozoic Udzha basin of the northern Siberian craton. We review the veracity of this hypothetical Belt-Purcell–Udzha basin as a test of our Siberia–west Laurentia reconstruction. Various elements of the structural framework of the basins are closely aligned in the reconstruction. The Udzha trough is aligned with the St. Mary–Moyie fault zone and Vulcan basement structure of southwestern Canada. The Khastakh trough is aligned with the Helena embayment of central Montana. Parts of the Belt-Purcell Supergroup appear to correlate with parts of the Riphean section in northeastern Siberia. However, the Siberian section appears to be much thinner than the Belt-Purcell section, and precise correlation is not possible with present stratigraphic and geochronological data. The reconstruction leads to the prediction that the Udzha rift channeled sediment from a cratonic pediment into the delta and alluvial fan complex in the deep Belt-Purcell rift-basin. Distributary channels may have shifted within the Udzha basin to feed shifting depocenters in the Belt-Purcell basin. Details of age and tectonic evolution for the Udzha basin are less clear than for the Belt-Purcell basin, but we outline specific geological relationships predicted by the reconstruction model, and suggest tests for future research.

Keywords: Laurentia; Siberia; Mesoproterozoic; Paleogeography; Belt-Purcell basin

1. Introduction

The Belt-Purcell basin, which straddles the Rocky Mountains at the Canada–USA border, was detached, displaced and tectonically "inverted" by Cordilleran thrusting (Price, 1981). One of the largest and deepest Mesoproterozoic basins in North America, the Belt-Purcell basin contains a 15–20 km thickness of sediments, sills, and volcanic flows (Harrison, 1972; Link, 1993; Cook and Van der Velden, 1995). It also contains significant deposits of lead, zinc, copper, cobalt, silver, and gold that have been mined for more than 100 years in the Sullivan, Couer d'Alene, Butte, and other districts.

The Belt-Purcell basin formed 300–400 Ma after consolidation of the Laurentian craton (Hoffman, 1988). It subsequently was truncated by the Neoproterozoic and Early Cambrian continental rifting that established the Cordilleran margin of Laurentia (Stewart, 1972). Sedimentological and de-

* Corresponding author. Tel.: +1-406-2432341; fax: +1-406-2432840.
E-mail address: jwsears@selway.umt.edu (J.W. Sears).

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trital geochronological data indicate that much of the terrigenous sediment in the basin was derived from the other craton (Frost and Winston, 1987; Cressman, 1989; Ross et al., 1992; Link, 1993; Ross and Villeneuve, 1998, 1999, 2001). The removal of the other craton has impeded understanding of the sedimentological and tectonic setting of the Belt-Purcell basin. The basin has been interpreted both as marine (Harrison, 1972) and lacustrine (Winston, 1991, 1999). Proposed tectonic settings include an aulacogen, a miogeoclinal re-entrant, an intracratonic basin, an impact basin, a successor basin, and a forearc basin (see Link, 1993).

Sears and Price (2000, 2003) proposed that conjugate cratonic partner of western Laurentia was the Siberian craton, and that the Udzha basin of the northeastern Siberian craton represents the counterpart of the Belt-Purcell basin. In this paper, we focus on the paleogeographic reconstruction of the Belt-Purcell and Udzha basins to gain insight into their mutual tectonic origin and evolution. We propose that the basins may have formed as parts of the same large intracratonic rift system. We suggest that the Udzha rift may have funneled sediment through tectonically controlled spillway channels into shifting distributary fans within the Belt-Purcell basin. The basin may have drained a large, low-relief region that included parts of the Siberian, Laurentian, and north Australian cratons. We use detailed maps of the Belt-Purcell–Udzha basin to pose regional- and continental-scale questions that may lead to new insights about the origin and evolution of the Belt-Purcell basin.

2. West Laurentia–Siberia connection

The Laurentian and Siberian cratons are generally thought to have formerly been connected in some way within the interior of a Proterozoic supercontinent (Ernst et al., 2000); however, published models link Siberia to Laurentia in a variety of different locations from southwestern USA to northern Greenland (Sears and Price, 1978; Hoffman, 1991; Condie and Rosen, 1994; Frost et al., 1998; Pelechaty, 1996; Rainbird et al., 1998; Khudoley et al., 2001; Scotese, 1992). Furthermore, rival models have identified west Laurentia's conjugate partner as the Siberian, south Australian, north Australian, Antarctic, and Cathaysian cratons, in part with smaller fragments inserted between the major cratonic plates (Sears and Price, 1978; Jefferson, 1978; Dalziel, 1991; Young, 1992; Ross et al., 1992; Karlstrom et al., 2001; Moores, 1991; Li et al., 1995; Borg and DePaolo, 1994). These various reconstructions are based on geological piercing points, rift-margin stratigraphy, detrital mineral provenance, and paleomagnetism.

At this stage of the investigation, the Siberia–Laurentia reconstruction issue remains open to discussion. Directly comparable key paleomagnetic poles for Proterozoic plate reconstructions are scarce (Buchan et al., 2001). However, paleomagnetic data of Elston et al. (2002) and Gallet et al. (2000) permit the late Mesoproterozoic Laurentia–Siberia configuration illustrated in Fig. 1. Paleomagnetic data of Wingate et al. (2002) restrict the Australian craton to a southern, AUSMEX configuration, where it could have been connected to the southern margin of the Siberian craton and to Mexico in a Siberia–Laurentia–Australia continental troika (Sears and Price, 2003). The inherent ambiguity of paleomagnetic data also permit the paleogeographic interpretation of Rainbird et al. (1998), in which the southeastern Siberian craton fits adjacent to Greenland. More detailed geologic tests, such as we present here, are needed to decide among paleomagnetic reconstructions. In Fig. 1 we illustrate the tight match of the correlative rifted margins of the northern Siberia and southwestern Laurentia, and the alignment of prominent Paleoproterozoic orogenic systems across the restored cratons that we have discussed in more detail elsewhere (Sears and Price, 2003).

3. Palinspastic reconstruction of Belt-Purcell basin

Most of the contents of the Belt-Purcell basin have been detached and displaced northeastward within the Phanerozoic Cordilleran thrust and fold belt (Price, 1981). It is necessary, therefore, to palinspastically restore Cordilleran tectonic displacements before attempting a detailed continental reconstruction. Price and Sears (2000) used a series of detailed balanced and restored cross-sections through the Cordilleran thrust and fold belt to construct a preliminary palinspastic map of the Belt-Purcell basin (Fig. 2). The thickest part of the Belt-Purcell Supergroup is restored into a

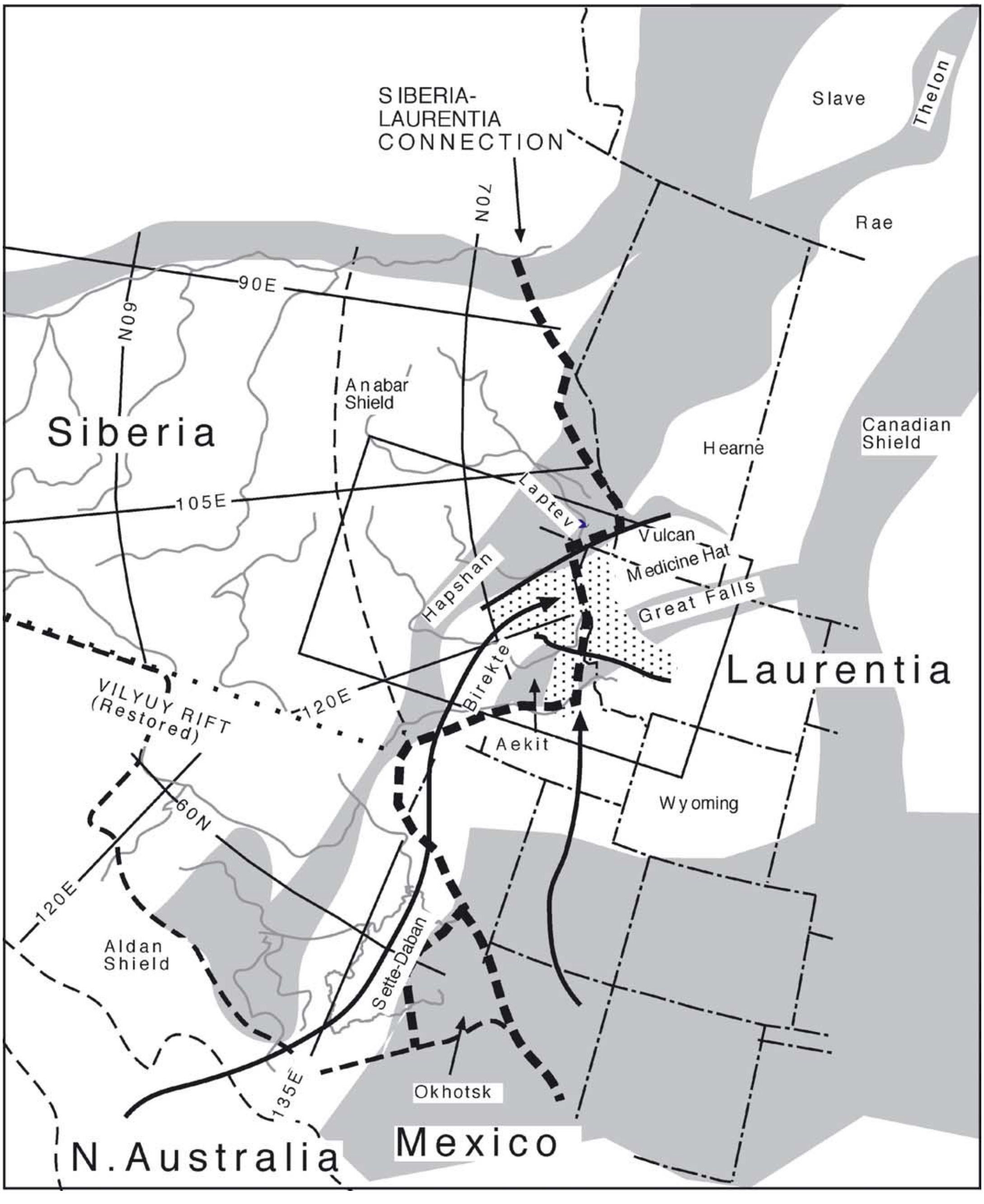

Fig. 1. Tectonic setting of Belt-Purcell and Udzha basins (stippled) in context of paleogeographic reconstruction of southwestern Laurentia with the northern Siberian craton. Drainages off the southwestern margin of Laurentia (arrows) may have linked sediment sources in northern Australia and southwestern Laurentia with Belt-Purcell basin. Shaded areas are Paleoproterozoic orogenic belts which link the cratons. Rectangle shows area of Figs. 2–7. Modified from Sears and Price (2003).

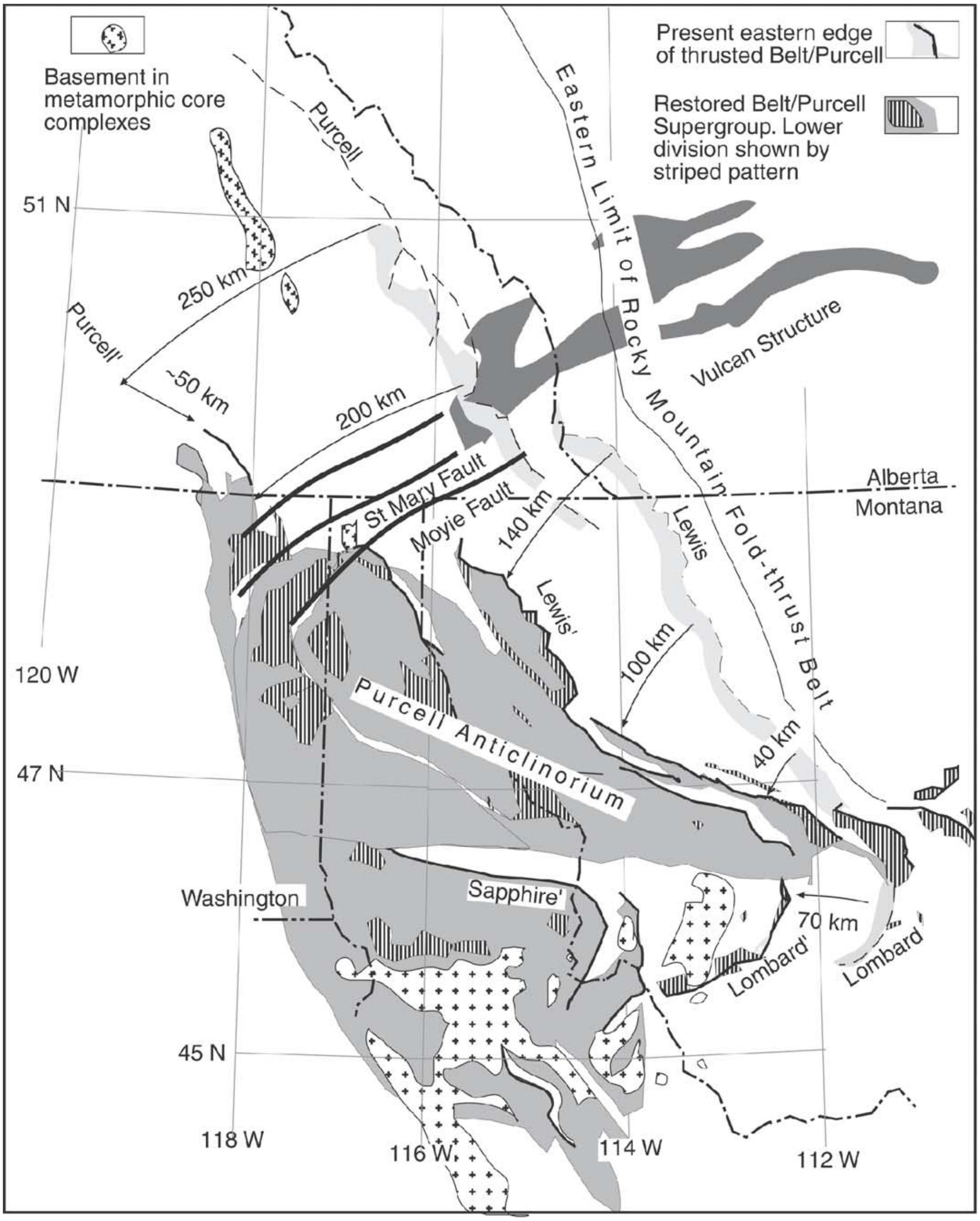

Fig. 2. Preliminary palinspastic restoration of Belt-Purcell basin. Constructed by restoring cumulative displacements of thrust plates as determined from balanced and restored cross-sections, after Price and Sears (2000) to compensate for Proterozoic extension across the St. Mary and Moyie faults. Positive aeromagnetic anomaly patterns of the Paleoproterozoic basement Vulcan structure (after Ross et al., 2000) in dark shading. This restoration is used to present data in Figs. 3–7. See Fig. 1 for approximate position of this map in Siberia–Laurentia-Australia restoration.

deep structural trough that crosses western Montana and Idaho. In Fig. 2, we have modified the map of Price and Sears (2000) by restoring the effects of Neoproterozoic and Cambrian extension in the region of the St. Mary and Moyie faults.

The Belt-Purcell basin is sharply truncated along the rifted western margin of Laurentia, where it was overlapped by continental rift and passive margin deposits of the Neoproterozoic–Phanerozoic Cordilleran miogeocline (Stewart, 1972). In our palinspastic restoration, the truncated edge of the basin approximately coincides with the $^{87}Sr/^{86}Sr = 0.704$ isopleth, a geochemical indicator of the location of the rifted western edge of Laurentian lithosphere (Armstrong, 1988). Isopachs and facies tracts of the Belt-Purcell Supergroup and associated dyke/sill swarms are truncated at the rifted margin on the restored base map, and thus provide links for paleocontinental reconstructions.

4. Belt-Purcell–Udzha basin configuration

Fig. 3 illustrates our reconstruction of the hypothetical Belt-Purcell–Udzha basin. The deepest part of the basin opened between the Aekit-Great Falls and the Hapshan–Vulcan Paleoproterozoic orogenic belts where the Mesoproterozoic rift system intersected the Archean Medicine Hat-Birekte terranes (Fig. 1). The Perry line normal-fault marks the southern side of the Belt-Purcell basin (McMannis, 1963), and the Laurentian rift-margin marks the western side. The northeastern side was a passive shelf draped by a thin sequence of stromatolitic carbonates and shallow-water or terrestrial siliciclastics (Link, 1993). A southern extension of the Belt-Purcell basin projects into the Yellowjacket region of central Idaho, but the intervening Cretaceous-Tertiary Idaho batholith obscures direct lithostratigraphic correlations with the main part of the basin.

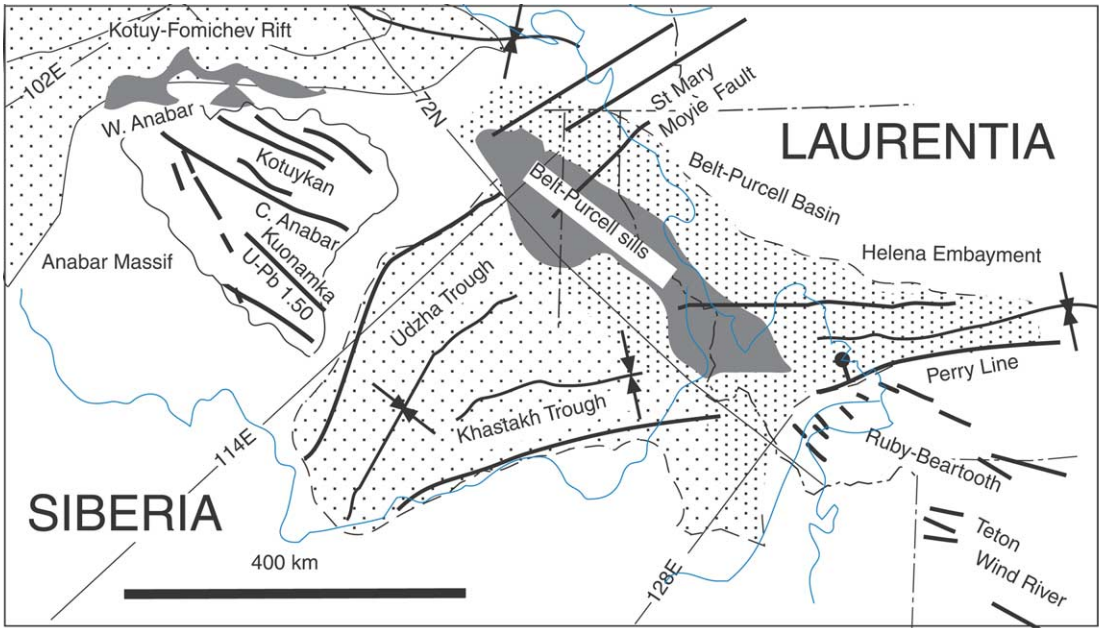

Fig. 3. Reconstructed Belt-Purcell and Udzha basin configuration at ca. 1450–1470 Ma. Belt-Purcell basin shown with heavier stipple. Crustal extension of Belt-Purcell basin schematically restored by overlapping Siberian and Laurentian geography. Pre- and early Belt-Purcell-aged Central Anabar, Kotuykan, and Kuonamka dyke swarms of Anabar massif align with Ruby, Beartooth, and Wind River dike swarms of Montana and Wyoming. Kuonamka swarm has U–Pb emplacement age of 1503 Ma (Ernst et al., 2000), which is inferred age of inception of Belt-Purcell rifting (Lydon, 2000). Belt-Purcell sills (shaded) align with sills in Kotuy-Fomichev rift on west flank of Anabar massif. St. Mary–Moyiefaults align with Udzha trough, and Helena embayment aligns with Khastakh trough. Anabar dikes and sills after Okrugin et al. (1990). Siberian basins after Surkov and Grishin (1997). Laurentian dikes after Chamberlain et al. (2000) and Harlan et al. (1997), restored according to Price and Sears (2000). See Fig. 1 for location in Siberia–west Laurentian restoration.

The Belt-Purcell basin is an approximate mirror image of the greater Udzha basin of northeastern Siberia. The Helena embayment of the Belt-Purcell basin, bounded by the Perry, Garnet, and Jocko syndepositional faults (Link, 1993), projects across into the Siberian Khastakh trough, as mapped by Surkov and Grishin (1997). The Siberian craton rift-margin defines the northern edge of the greater Udzha basin, and corresponds to the Laurentian rift-margin in Fig. 3. The western edge is the Udzha trough proper, a Riphean rift that follows the ca. 2.0 Ga boundary between the Hapshan and Birekte basement provinces (Zonenshain et al., 1990; Rosen et al., 1994; Smelov et al., 2001).

The Udzha trough trends into an abrupt, 200 km offset of the northern margin of the Siberian craton at the Laptev Sea (cf. Zonenshain et al., 1990; Rosen et al., 1994; Kosygin and Parfenov, 1975; Surkov et al., 1991). As shown in Fig. 3 this offset fits against an equivalent 200 km jog in the Cordilleran miogeocline defined by the St. Mary–Moyie fault zone (Price, 1981). This major transverse structure was active during Belt-Purcell deposition, during Neoproterozoic Windermere rifting, during Early Cambrian opening of the Eager trough, and during Devonian tectonism (Price and Sears, 2000). It was reactivated as a Mesozoic transpressive dextral shear zone, and was intruded by mid-Cretaceous granites (Price, 1981). It appears to have formed by reactivation of the Paleoproterozoic Vulcan basement structure, which is expressed by prominent aeromagnetic and gravity anomaly trends in the Alberta subsurface. Eaton et al. (1999) interpreted the Vulcan structure as ca. 2.0 Ga continental collisional zone. The relationship of the St. Mary–Moyiefaults to the Vulcan structure matches that of the Udzha trough to the Hapshan boundary structure. The reconstructed Vulcan–St. Mary–Moyie–Udzha trend has a combined length of >600 km.

The St. Mary–Moyie–Udzha faults may have compartmentalized a complex Mesoproterozoic intracratonic rift-basin system. Surkov and Grishin (1997) mapped the 6–8 km deep Kotuy-Fomichev rift on the northwestern flank of the Anabar massif, west of the Udzha basin. On our paleogeographic reconstruction (Fig. 3), the axis of this rift is aligned with the Belt-Purcell basin. Surkov et al. (1991) and Rosen et al. (1994) show that the Taimyr trough, which lies farther northwest, is 10–15 km deep. It contains Riphean strata, but most of this great thickness comprises foreland-basin fill of the Phanerozoic Taimyr orogen.

5. Reconstructed Belt-Purcell and Anabar dike and sill swarms

The Kotuykan and Central Anabar dyke swarms trend across the region of the reconstructed basins from the Anabar massif of northern Siberia to the Ruby, Beartooth, Teton, and Wind River swarms of southwest Montana and adjacent Wyoming (Fig. 3). These dyke swarms may record crustal extension associated with initiation of the main rift basin. Lydon (2000) estimated the time of initiation of the Belt-Purcell basin at between 1510 and 1485 Ma, by extrapolation of a plot of zircon U–Pb age dates against cumulative thickness of Belt-Purcell strata. The overall age range of the exposed part of the Belt-Purcell Supergroup is about 1500–1350 Ma (Evans et al., 2000; Lydon, 2000). Most of the K–Ar whole-rock ages reported from the Anabar massif dike swarms cluster between 1500 and 1350 Ma (Okrugin et al., 1990). This range overlaps a significant number of K–Ar ages from Montana and Wyoming dykes (Harlan et al., 1997). However, more precise and directly comparable U–Pb geochronological data are needed to verify correlations among these dykes. A dyke in the Wind River Mountains of Wyoming has been dated at 1470 Ma (U–Pb, Chamberlain et al., 2000). The Kuonamka mafic dyke swarm in the Anabar shield yielded a provisional U–Pb baddeleyite emplacement age of 1503 ± 5 Ma (Ernst et al., 2000). Collectively, the dykes may form a 1000 km long swarm, with the Belt-Purcell–Udzha basin near its mid-point.

As discussed in a later section, the Chieress dikes of Siberia and Salmon River complex of Idaho have correlative U–Pb ages of 1.37–1.38 Ga (Ernst et al., 2000; Doughty and Chamberlain, 1996). These plot adjacent to one another on our reconstruction.

Widespread mafic sills intruded the Belt-Purcell Supergroup and northern Siberian Riphean strata. The Belt-Purcell sills are concentrated in a narrow zone along the axis of the Belt-Purcell basin (Höy et al., 2000). In our paleogeographic reconstruction (Fig. 3), the zone of Belt-Purcell sills is aligned with a concentration of thick dolerite sills on the west flank of the Anabar massif, in the Kotuy-Fomichev rift (Okrugin et al., 1990; Surkov and Grishin, 1997). Geochronological data do not presently allow precise correlation among the sills. The 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). Many of the lower Belt-Purcell sills were injected into wet sediments of the Prichard and Aldridge formations, where they created unusual interference structures and mobilized base metals (Höy et al., 2000; Sears et al., 1998). Anderson and Parrish (2000) interpreted 1497 Ma (U–Pb) exogenous zircons in the St. Joe tuff as indication that sills that occur below the deepest exposed levels and have been imaged by seismic reflection (Cook and Van der Velden, 1995), may date to 1497 Ma. These zircons could, however, also be interpreted as xenocrysts of detrital zircon grains (Ross, written communication, 2003). The sills on the west flank of the Anabar shield yield K–Ar ages as old as 1453 Ma (Okrugin et al., 1990). Further work is needed to determine whether the west Anabar sills were syndepositional, and to determine their U–Pb emplacement ages. Other Mesoproterozoic sills or flows occur within the Udzha trough; preliminary K–Ar whole-rock ages from 1150 to 1320 Ma are reported (Khain, 1985).

6. Belt-Purcell basin

The stratigraphy and sedimentology of the Belt-Purcell Supergroup has been studied in more detail than that of the Riphean of the northern Siberian craton, mainly because of more accessible exposures. Sedimentological trends and patterns outlined in the Belt-Purcell Supergroup provide criteria for future tests of correlations between the Belt-Purcell Supergroup and the northern Siberian Riphean system.

The Belt-Purcell Supergroup is >15 km thick along the basin axis; and the base is not exposed there (Link, 1993). The Belt-Purcell Supergroup comprises four main stratigraphic divisions. These are, from the base up: the lower Belt-Purcell Supergroup, the Ravalli Group, the middle Belt carbonate, and the Missoula Group. The lower units were deposited during the active rift stages, and the overlying units during thermal sagging of the basin (Cressman, 1989; Sears et al., 1998; Chandler, 2000; Lydon, 2000).

6.1. Lower Belt-Purcell Supergroup

The lower Belt-Purcell Supergroup, which includes the Prichard Formation in the USA, and the Fort Steele and Aldridge Formations in Canada, is >6 km thick, and is dominated by deep basinal turbiditic muds, silts and sands, with intercalated syndepositional mafic sills along the central axis of the basin. These deeper water turbiditic deposits are replaced along the northeast margin of the basin by the thinner, shallow-water shelf-facies comprising the Haig Brook, Tombstone Mountain, Waterton and Altyn Formations, which consist mainly of carbonate rocks, including stromatolitic dolomite, and near the top, arenaceous dolomite and coarse-grained quartz arenite (Price, 1964; Fermor and Price, 1983; Whipple, 1992). To the south, along the Perry line fault (Fig. 4), mass-flow breccias and diamictites of the LaHood Formation, eroded from adjacent Archean basement rocks, are intercalated with the turbidites of the Prichard Formation (McMannis, 1965). Cressman (1989) showed that members A–E of the Prichard Formation record upward shoaling, member F records rapid tectonic collapse, and members G–H record a second upward shoaling. The basin collapse at the E–F boundary was accompanied by widespread intrusion of mafic sills, faulting, slumping, fluid overpressure, mud diapirism, and a northwestern shift in the depositional center (Cressman, 1989; Sears et al., 1998; Höy et al., 2000). Contemporaneous deposition of exhalative massive sulphides produced the world-class Zn–Pb–Ag Sullivan ore body (Höy et al., 2000). As noted above, the sills associated with this event have been U–Pb dated at about 1470 Ma throughout the basin (Anderson and Davis, 1995; Sears et al., 1998; Höy et al., 2000).

Syndepositional faulting occurred along a system of northeast-trending transform faults that segmented the central rift axis of the Belt-Purcell basin into individual sub-basins (Höy et al., 2000). Tectonic inversion of these sub-basins during Cordilleran thrusting produced culminations along the Purcell anticlinorium. On the opposite side of our Siberia–Laurentian connection, the transform faults merge directly with Mesoproterozoic rifts mapped by Zonenshain et al. (1990) and Surkov and Grishin (1997). Surkov et al.

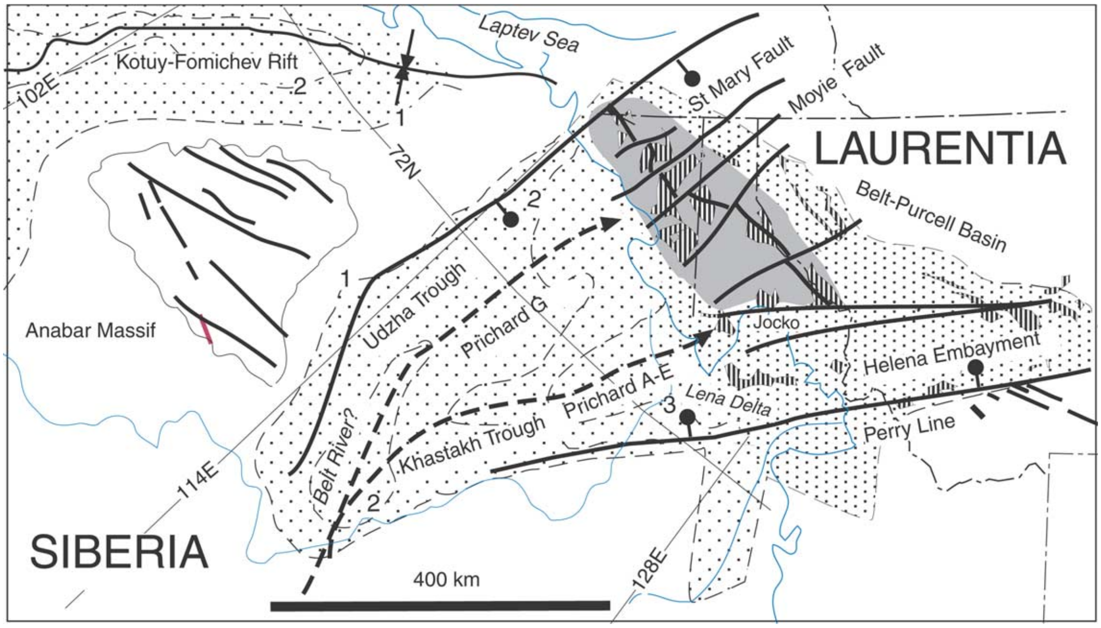

Fig. 4. Lower Belt-Purcell Supergroup (vertical ruling). Shaded area is extent of Prichard G-middle Aldridge fan (after Höy et al., 2000). Belt-Purcell transform faults align with Udzha and Khastakh troughs of Siberia. Sources of Prichard fans coincide with Udzha and Khastakh troughs, suggesting tectonic spillways of Belt river. Prichard G-middle Aldridge fan sediment-input point after Cressman (1989), on palinspastic map of Belt-Purcell basin (Fig. 2). Belt-Purcell rift axis and transform faults modified after Höy et al. (2000) and Link (1993). Siberian isopachs in kilometers, after Surkov and Grishin (1997). See Fig. 1 for location in Siberia–west Laurentian restoration.

(1991) mapped the "lower structural stages" of the Udzha and Khastakh troughs, using potential field data. These early-rift stages are likely early Riphean (older than 1350 Ma) in age, and may be equivalent to the early-rift stages of the lower Belt-Purcell Supergroup.

Price (1964) interpreted the very large volume of fine-grained clastic sediment in the lower Belt-Purcell Supergroup as the deposit of a large river that drained a low relief, continental-scale basin. Cressman (1989) showed that depocenters for the lower and upper members of the Prichard Formation shifted about within the basin. Using paleocurrent measurements from the Prichard G member and middle Aldridge Formation, Cressman (1989) located the mouth of the hypothetical Belt River at a distinct point adjacent to the rifted southwest side of the basin. In our reconstruction, Cressman's sediment-input point coincides with the truncated end of the Udzha trough; the Belt drainage shown in Fig. 4 is essentially that portrayed by Cressman (1989). We suggest that the Udzha trough captured the drainage of a large basin that included parts of the Siberian craton, Laurentia, and northern Australia. Rapid erosion of a fine-grained sediment veneer within this basin would explain rapid deposition of the large volume of fine-grained sediment in the lower Belt-Purcell Supergroup (cf. Lydon, 2000).

6.2. Ravalli Group

The Prichard Formation grades upward, through a thick transition unit, into the shallow-water to terrestrial Ravalli Group. The Revett Quartzite of the Ravalli Group represents a widespread terrestrial clastic wedge. This distinctive quartzite thickens westward along the axis of the basin on the palinspastic map. Winston (1991) showed that it also coarsens westward, and represents a collection of tabular sand beds brought in by sheet floods from a cryptic western cratonic source. It is flooded with fine-grained detritus characterized by 1510–1610 Ma zircons (Ross, written communication, 2003). These could have been derived from source rocks of this age range in the Coen,

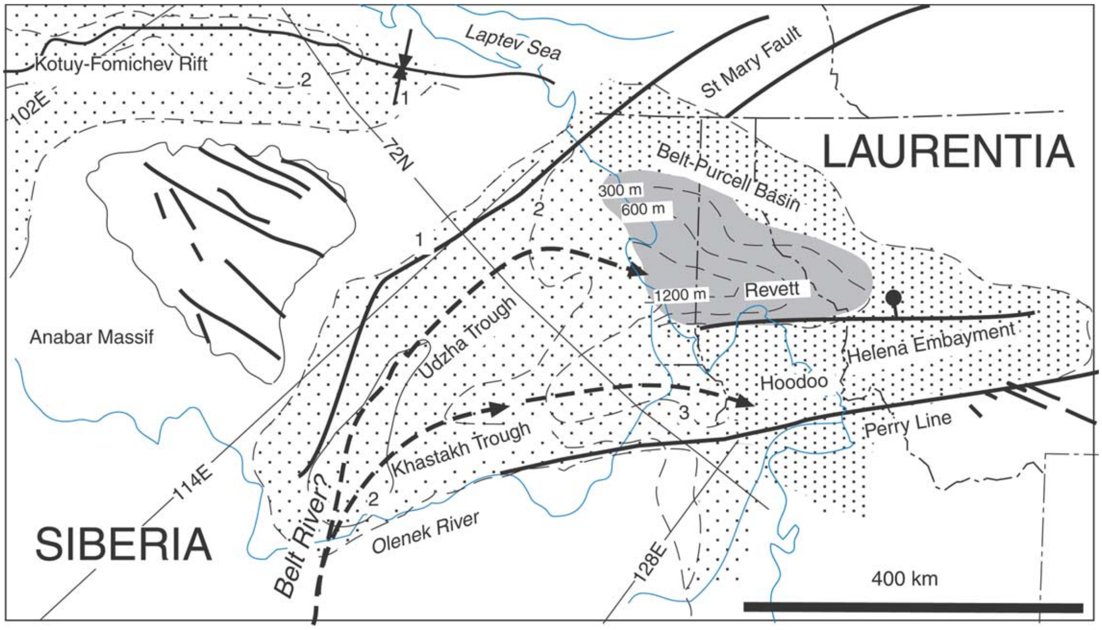

Fig. 5. Ravalli Group of Belt-Purcell Supergroup (heavier stipple) compared with Riphean of northern Siberian craton (lighter stipple). Belt-Purcell basin shown with heavier stipple. Shaded area is Revett fan, isopachs after Harrison (1972). Udzha trough may have been spillway for Revett Quartzite. Khastakh trough may have been spillway for Hoodoo fan. See Fig. 1 for location in Siberia–west Laurentian restoration.

Georgetown, Mt. Isa, and McArthur domains of northern Australia (Blewett et al., 1998; Page et al., 2000), which, in our reconstruction, occur at the at the head of the drainage basin (Figs. 5 and 1).

6.3. Middle belt carbonate

The middle Belt carbonate, which overlies the Ravalli Group, has distinct facies tracts reminiscent of those of the lower Belt-Purcell Supergroup (Figs. 6 and 7). A stromatolitic carbonate shelf on the northeastern margin of the basin passed southwestward into thick subaqueous siliciclastic rocks of the Wallace Formation, and mass-flow breccias follow the southwestern basin margin (Link, 1993). Like the Revett Quartzite, the Wallace Formation thickens, coarsens, and has increasing siliciclastic content westward along the basin axis. It also requires a provenance on the conjugate craton west of Laurentia (Winston, 1999). The Wallace Formation also contains abundant fine-grained 1510–1610 Ma detrital zircons (Ross, written communication, 2003). As with the lower Belt-Purcell Supergroup, the silicilastic input points coincide with the Udzha and Khastakh troughs on our reconstruction. Winston (1999) interpreted the Wallace Formation as the storm-dominated lacustrine deposit of a shallow lake that expanded and contracted in response to flooding events. The Wallace breccias may have been produced by faulting accompanying renewed subsidence along the Perry line fault. Middle Belt carbonate also appears to occur south of the Perry line in central Idaho in part of the Yellowjacket Formation, perhaps representing a separate fan (Link, 1993).

6.4. Missoula Group

The Missoula Group clastic wedges becomes thinner and finer grained northward, (Winston, 1986), and paleocurrents indicate northward transport (Wallace, 1999). It appears to be equivalent to the thick Lemhi Group of central Idaho (Link, 1993). The lower Missoula Group contains the 1443 Ma (U–Pb) Purcell lava, probably related to renewed rifting (Evans et al., 2000). Ross and Villeneuve (1999) showed that the Missoula Group records a change in provenance with

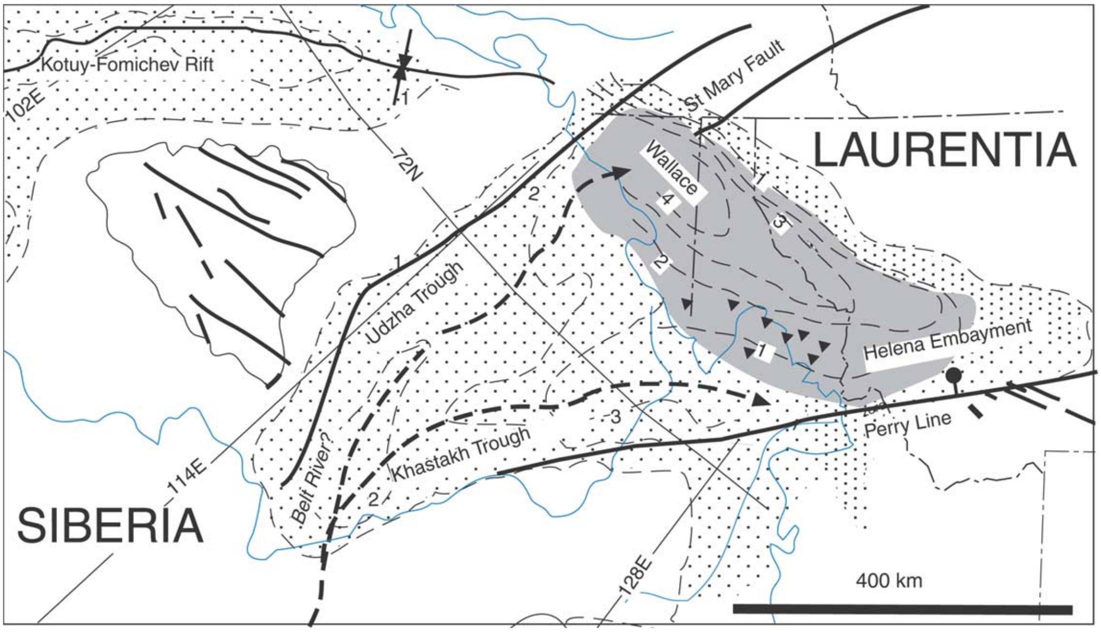

Fig. 6. Middle Belt Carbonate of Belt-Purcell Supergroup (heavier stipple) compared with Riphean of northern Siberian craton (lighter stipple). Shaded area is Wallace Formation clastic wedge. Udzha trough may have been spillway for Wallace siliciclastics. Facies after Link (1993), isopachs in kilometers after Harrison (1972). See Fig. 1 for location in Siberia–west Laurentian restoration.

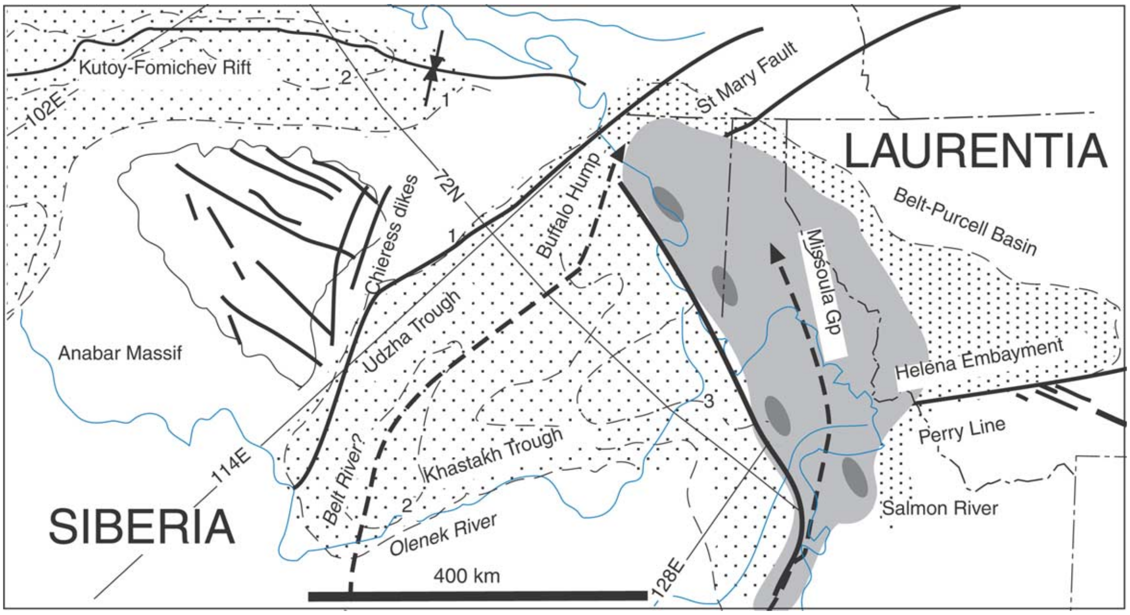

Fig. 7. Missoula Group and Buffalo Hump Formation clastic fans. Note also Cheiress dikes on east Anabar massif and Salmon River intrusives in western Belt-Purcell basin (cf. Okrugin et al., 1990; Doughty and Chamberlain, 1996). See Fig. 1 for location in Siberia–west Laurentian restoration. Darker shading gives locations of 1.37–1.38 Ga mafic magmatism and metamorphism in Laurentia that may correlate with Cheiress dykes of Siberia.

loss of the exotic 1510–1610 Ma detrital zircons, which were replaced by abundant ca. 1400 Ma zircons that could have had sources in southwest Laurentia. Conglomerates containing basement clasts, which occur in the southwest, may indicate propagation of rifting toward the southeast, capturing a new sediment source that then flowed into the basin through a new spillway.

6.5. Buffalo Hump Formation

The Buffalo Hump Formation of the Deer Trail Group is restricted to isolated exposures on the west edge of the Belt-Purcell basin, where it unconformably overlies rocks that Link (1993) assign to the Belt-Purcell Supergroup. It contains conglomeratic quartz–arenite and feldspathic siltite and argillite, and contains ca. 1100 Ma detrital zircons (Ross et al., 1992). It could represent further deposition from the Belt river, with headwaters in the ca. 1100 Ma Grenville Province of southwest Laurentia. It is noteworthy that the Mayamkan Formation of southeastern Siberia also contains Grenville-aged detrital zircons (Rainbird et al., 1998), that are consistent with linkage along the Belt river of Fig. 1.

7. Northern Siberian Riphean strata

Relatively small outcrop areas within the Udzha trough, Olenek uplift, and Kharaulakh Mountains expose about 1–2 km of Riphean strata, and Riphean strata also flank the Anabar massif in wide areas on its west and east sides (Parfenov and Kuzmin, 2001). These could provide a host of potential tests for the reconstruction that we have proposed, but few details are known from them. Fig. 8 presents a stratigraphic cross-section of the northern Siberian Riphean system from the west flank of the Anabar massif to the Kharaulakh Mountains. The Riphean system comprises four main divisions, and is overlain with regional angular unconformity by the Vendian Yudoma Group. The classic divisions of the Siberian Riphean system comprise (from the base up): the Uchur, Aimchan, Kerpyl, and Lakhanda groups (cf. Khudoley et al., 2001). The Uchur Group is lower Riphean (1600–1350 Ma), the Aimchan and Kerpyl groups are middle Riphean (1350–1050 Ma), and the Lakhanda Group is upper Riphean (1050–680 Ma). Of these, parts of the Uchur and Aimchan groups are the most likely possible Belt-Purcell Supergroup correlatives, because the Belt-Purcell Supergroup was

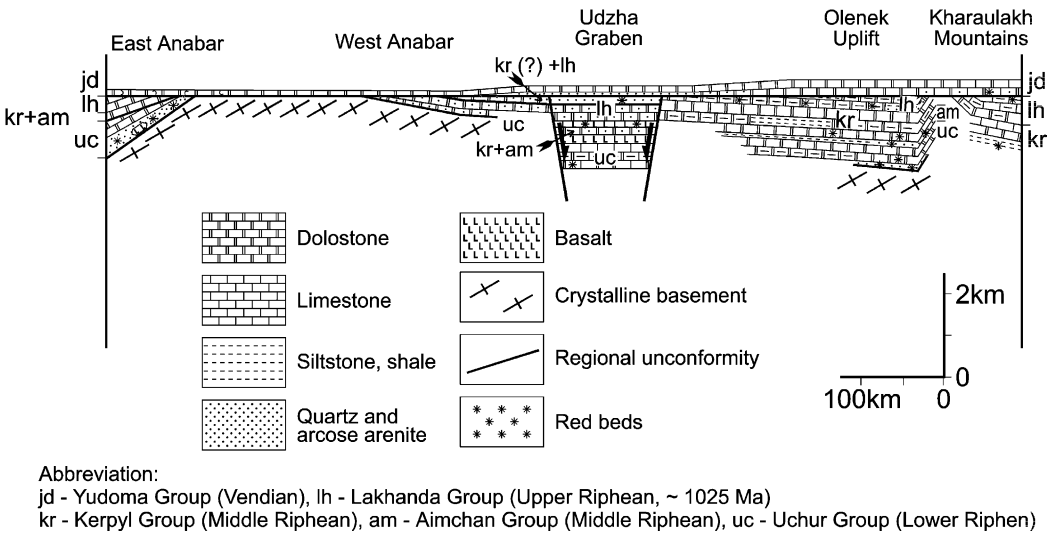

Fig. 8. Stratigraphic section across northern Siberian Riphean system. Uchur Group is approximate equivalent of Belt-Purcell Supergroup. Basalt in Udzha graben upper Uchur Group may be correlative with Purcell lavas, or perhaps Salmon River complex. Kerpyl Group is of uncertain correlation at this time. Lakhanda Group may correlate with Buffalo Hump Formation. Compiled by Khudoley from Semikhatov and Serebryakov (1983), Shenfil (1991), Parfenov and Kuzmin (2001), and unpublished data.

deposited from 1500 to 1350 Ma (Evans et al., 2000; Lydon, 2000).

7.1. East flank Anabar massif and Udzha trough

The Riphean rocks on the east flank of the Anabar massif unconformably overlie Archean to lower Proterozoic crystalline basement rocks. The section is up to 1.5 km thick and contains several formal formations, separated from each other by unconformities. Red cross-bedded sandstones predominate in the lower part of the section, whereas stromatolitic dolomites are typical for the upper part. A significant part of the section is cut by the Chieress dike swarm, and thus is older than 1380 Ma (U–Pb, baddeleyite, Ernst et al., 2000), although the uppermost unit of stromatolites is usually considered to be a correlative of a part of the Kerpyl and Lakhanda groups. Most of the east Anabar section may correlate with that on the northeast side of the Belt-Purcell basin.

The stratigraphy of the Udzha trough was developed in 1970s and early 1980s, and since that time no intense studies have been undertaken (Semikhatov and Serebryakov, 1983; Shenfil, 1991; Parfenov and Kuzmin, 2001). The section is overlain with sharp unconformity by Vendian sandstone. The 1.6 km section is divided into four units, with the Ulakhan-Kurung Formation at the base, and the Udzha Formation at the top.

The Ulakhan-Kurung Formation is a 600 m thick dolomite with some stromatolite units. The base is not exposed. It is overlain unconformably by the 500 m thick Unguokhtakh Formation, which comprises basaltic tuffs with subordinate mafic sills (or flows), dolomite, terrigenous breccia, and fine-grained terrigenous rocks, which increase in abundance upward. Very old analytical data indicate that K–Ar whole-rock ages of sills and tuffs range from 1320 to 1150 Ma (Khain, 1985). The Unguokhtakh Formation is unconformably overlain by the 300 m thick Khapchanyr Formation, which is made up of dolomite with some fine-grained terrigenous rocks, which increase in abundance upward. The Udzha Formation is about 200 m thick and comprises terrigenous rock with some dolomite at the top. Sandstone predominates, but there is some conglomerate at the base.

This section differs greatly from others exposed close to it. For example, the basaltic tuffs of the Unguokhtakh Formation pinch out abruptly both westward and eastward. Further east, on the Olenek uplift, their possible correlatives appear again. Although there is no precise age control on the Udzha section, the Khapchanyr and Udzha formations are considered by most researchers to be correlatives of the Lakhanda Group of southeastern Siberia, which is older than 1005 Ma (Rainbird et al., 1998), and is estimated to have been deposited at ca. 1025 Ma according to Pb–Pb dating of carbonates (Semikhatov et al., 2000). The Ulakhan-Kurung Formation is usually considered to be a part of the lower Riphean and is likely older than 1350 Ma.

7.2. Olenek uplift section

A 2 km thickness of the Khastakh trough-fill is exposed on the Olenek uplift. The Uchur Group unconformably overlies Lower Proterozoic basement and contains redbeds, sandstone, dolomite, and shale. The overlying Middle and Upper Riphean section is dominated by arenaceous dolomite.

7.3. Kharaulakh Mountains section

This section occupies a fold structure that lies outboard of the Siberian craton and thus palinspastically restores somewhat to the east of the Lena River. The Siberian connection reconstruction places these rocks adjacent to the Yellowjacket extension of the Belt-Purcell basin. The base is not exposed in the Kharaulakh Mountains, but the lowest exposures appear to include the Uchur Group. There appears to be a significant angular unconformity beneath the Vendian Yudoma Group, indicating tectonic activity prior to the Neoproterozoic (Pelechaty, 1996).

7.4. Kotuy-Fomichev and Taimyr troughs

Thick Mesoproterozoic strata and sills emerge along the southern margin of the Kotuy-Fomichev rift on the west flank of the Anabar massif (Fig. 3) (cf. Okrugin et al., 1990). The Uchur Group rests with profound unconformity on the Archean basement, and is overlain with angular unconformity by the Kerpyl Group (Fig. 8). The Uchur Group contains basal red beds, quartzose and feldspathic arenites, and basaltic sills and dolomites, and thickens westward into the

Kotuy-Fomichev rift. Evidently, the rift was active during early Riphean, with uplift of the Anabar massif. The middle and upper Riphean is dominated by arenaceous dolomite.

Isopachs of the Kotuy-Fomichev troughs are truncated at the Laptev Sea transverse fault (Fig. 1) (cf. Surkov et al., 1991).

8. Belt-Purcell Supergroup correlations with northern Siberian sections

Without further study of the northern Siberian Riphean section, there is little upon which to base a precise stratigraphic correlation with the Belt-Purcell Supergroup; however, some general correlations can be suggested. The lower Riphean section on the east flank of the Anabar massif is cut by the Chieress dyke swarm, and thus is older than 1380 Ma (U–Pb, Ernst et al., 2000). It may represent a thin, platformal section correlative with that on the northeast side of the Belt-Purcell basin. It comprises arenaceous dolomites similar to the Altyn dolomite of the eastern Belt-Purcell basin.

The Khapchanyr and Udzha formations of the Udzha trough section may post-date the Belt-Purcell Supergroup. The ca. 1020–1040 Ma sandstone and conglomerate of the Udzha Formation may correlate with the Buffalo Hump Formation quartzite and conglomerate, which also contains ca. 1100 Ma detrital zircons (Ross et al., 1992). The Ulakhan-Kurung Formation may be equivalent to the middle Belt carbonate, and the Unguokhtakh Formation may be equivalent to the Purcell lavas. Conversely, the Unguokhtakh Formation could equate with the Salmon River mafic igneous province, which yielded a 1370 Ma U–Pb age (Doughty and Chamberlain, 1996). No field work has been undertaken in the Udzha section since the early 1980's. More precise geochronology on the tuffs and sills (or flows) of the Unguokhtakh Formation, and detailed study of the paleocurrents and detrital-zircon systematics of the terrigenous strata of the Udzha section would provide critical tests of these predictions from the hypothetical northern Siberian–southwestern Laurentia connection.

There is an excellent U–Pb age correlation between outbreaks of mafic magmatism at ca. 1.37–1.38 Ga in central Idaho and the eastern Anabar shield. The Salmon River complex is a 2 km thick, layered-mafic body with associated granophyre and rapakivi granite (Doughty and Chamberlain, 1996; Evans et al., 2000). It appears to be intrusive at a shallow level into the Yellowjacket Formation, which is thought to be correlative with the upper part of the Belt-Purcell Supergroup (Evans et al., 2000). Several other locations within the Belt-Purcell basin have yielded dates of about the same age, referred to the East Kootenay orogeny by McMechan and Price (1982). Anderson and Parrish (2000) and Evans et al. (2000) suggested that the East Kootenay orogeny was a thermal event associated with renewed rifting and magmatism in the Belt-Purcell basin, at or near the end of Belt-Purcell deposition. The coeval Chieress dyke swarm intruded basement rocks and overlying Mesoproterozoic strata on the flank of the Udzha trough, and is subparallel with the trough. It yielded a precise U–Pb baddeleyite emplacement age of 1384 ± 2 Ma (Ernst et al., 2000). In our reconstruction (Fig. 7) the Chieress dyke swarm is located within 200 km of the 1.37 Ga Salmon River complex of Idaho and of correlative intrusive and metamorophic rocks in the western parts of the Belt-Purcell basin (Doughty and Chamberlain, 1996; Evans et al., 2000; Lydon, 2000).

9. Discussion and conclusion

The available data are compatible with our reconstruction of a hypothetical Belt-Purcell–Udzha basin, but directly comparable, precise geochronological, stratigraphic, and sedimentological data from both cratons are rare. Only the U–Pb data from the Kuonamka and Chieress dyke swarms and Belt-Purcell sills and Salmon River complex are directly comparable with respect to laboratory research methods and standards.

Given the uncertainties in the reconstruction, the Belt-Purcell–Udzha basin is consistent with the notion of Winston (1991) that the Belt-Purcell Supergroup was deposited in a closed or restricted intracratonic basin. The sediment sources indicated by stratigraphic and sedimentological studies on several units are consistent with capture of sediment flux by the Udzha trough and rapid deposition in the Belt-Purcell rift.

Could the Udzha and Khastakh troughs have formed spillway channels of a large river that drained a broad basin? Potentially correlative strata appear to be significantly thinner in northern Siberia than in the Belt-Purcell basin; they may define regions of sediment by-pass rather than sediment accumulation. By contrast, the Belt-Purcell basin was underlain by thick mafic sills and attenuated crust (Cook and Van der Velden, 1995), which could accommodate more sediment. Perhaps the Siberian side represents the uplifted footwall, and the Laurentian side the attenuated hangingwall of an intracratonic rift basin.

The depocenters and terrigenous sediment spillways appear to have shifted about within the basin during deposition of Prichard members A–E, Prichard member G, the Revett Quartzite, the Wallace Formation, and the Missoula Group, perhaps as a result of tectonism in the Udzha and Khastakh troughs (Figs. 4–7). The Prichard A–E and Revett fans may have been controlled by the Khastakh channel. The Prichard G and Wallace fans may have followed the Udzha channel. The Missoula Group fan may have been controlled by a new Kharaulakh channel from the south, perhaps due to renewed rifting punctuated by the Purcell lava and Salmon River complex. Sediment initially accumulated rapidly in deltaic turbidity deposits along the axis of the deep Belt-Purcell rift-trough, where it was intruded by syndepositional mafic sills. As the basin shoaled, the delta evolved into an alluvial fan system. The isostatic load of the sediment and thermal sagging may have caused the basin to broaden, permitting accumulation of shelf-facies along the margins.

The Udzha rift may have captured and focussed sediment flux from a large pediment that was destabilized by Belt-Purcell–Udzha rifting. An existing pediment veneer of silt and mud could have been rapidly eroded and redeposited in the Belt-Purcell rift as the lower Prichard and Aldridge formations. Massive sheet floods interpreted to have deposited tabular sandstone beds of the Revett Quartzite (Winston, 2002) could represent run-off from the large drainage basin that was funnelled into the Belt-Purcell basin by the Udzha and Khastakh spillways.

Extensive U–Pb detrital zircon and monazite data show that the fine-grained, west-derived siliciclastics of the Belt-Purcell Supergroup had provenance in regions of late Archean, late Paleoproterozoic, and early Mesoproterozoic crystalline rock (Ross et al., 1991, 1992; Ross and Villeneuve, 1998, 1999, 2001). Crystalline rocks in the Coen and Georgetown inliers and Mt. Isa and McArthur basins of northern Australia provide good matches for most of these (cf. Blewett et al., 1998; Page et al., 2000). The hypothetical Belt river, flowing across the Siberia–Laurentia–Australia troika (Fig. 1) could have connected source rocks in northern Australian headwaters with depositional sites in the Belt-Purcell basin. Such a river may have flowed through the Sette-Daban trough in southeast Siberia and the Udzha trough in northeast Siberia (Fig. 1). A detailed U–Pb study of detrital-zircon ages of Siberian Riphean strata that are correlative with the Belt-Purcell Supergroup could provide a test of our reconstruction. Detrital-zircon age data are available for the Riphean Uchur, Kerpyl, and Uy groups of the Sette-Daban trough (Rainbird et al., 1998; Khudoley et al., 2001), but not for the Udzha trough. The sampled part of the Uchur Group may predate, and the Kerpyl Group may post-date the Belt-Purcell Supergroup, and the intervening Upper Uchur Groups and Aimchan Group, likely Belt-Purcell correlatives, have not been analyzed.

The Uchur Group is bracketed to 1650–1350 Ma, and thus is potentially correlative with the 1500–1350 Ma Belt-Purcell Supergroup (Evans et al., 2000; Lydon, 2000), or the older Neihart Quartzite (Link, 1993). Detrital zircons from the lower Belt are mainly Archean, with significant Paleoproterozoic grains ranging from 1876 to 1776 Ma (Ross and Villeneuve, 1998). There is some similarity between the Prichard/Aldridge formations and Uchur Group in that they both contain ca. 1700–1900 Ma detrital zircons; these could reflect common source terranes within the postulated drainage basin. However, the Uchur Group lacks 2600 Ma detrital zircons, and the Prichard/Aldridge formations have scarce 2000 and 2100 Ma zircons, which are common in the Uchur Group. These differences may argue against the Siberia–west Laurentian connection; the Uchur Group zircons better match Sequence A detrital zircons in the Canadian Northwest Territory (Khudoley et al., 2001). However, the data come from the base of the Uchur Group, and may be more comparable with the Neihart Quartzite than the Belt-Purcell Supergroup.

Zircons having the unusual age range of 1510–1610 Ma appear in the Prichard E member, and persist upwards through the Ravalli Group and middle Belt carbonate (Ross and Villeneuve, 1999). The Aimchan Group has not been analyzed, but the late

Riphean Kerpyl Group of southeastern Siberia also has a detrital-zircon age spectrum that includes a 1510–1610 Ma peak. These detrital zircons appeal to a provenance beyond Laurentia and Siberia (Ross et al., 1991, 1992). The Kerpyl Group is younger than most of the Belt-Purcell Supergroup (cf. Semikhatov et al., 2000), but both groups require a similar exotic source terrane, perhaps the northern Australian craton (cf. Blewett et al., 1998; Page et al., 2000). The Kerpyl Group also contains detrital zircons as young as 1300 Ma, that could have provenance in southwest Laurentia (Khudoley et al., 2001).

The Uy Group and Buffalo Hump Formation both contain 1050–1250 Ma zircons (Ross et al., 1992; Rainbird et al., 1998) that may have had a common source in the Grenville orogen of southwest Laurentia; however, Rainbird et al. (ibid.) proposed that 1.2–1.0 Ga detrital zircons in immature Mesoproterozoic redbeds in southeast Siberian sections may have been derived from Greenland.

Detrital-zircon ages from the Uchur Group-equivalent units of northern Siberia are required to further test this hypothesis. Because these rocks plot directly adjacent to the Belt-Purcell Supergroup along the northern Siberia–southwestern Laurentia connection, they might be expected to have similar detrital zircon age-spectra.

The late Mesoproterozoic Midcontinent rift of Laurentia provides an example of a cratonic rift, such as we have postulated for the Belt-Purcell basin; the thickness of the fill within it approaches the total thickness of the crust and it includes abundant mafic flows and intrusives, as well as thick lacustrine and terrestrial sediments.

The temporal relationship of the postulated Belt-Purcell–Udzha basin and the Kotuy-Formichev and Taimyr troughs is unknown. Although they may have been evolving coevally, they may not have been linked or perhaps only were linked through small tectonic channels across transform faults. For example, the sheet floods that swept across the Belt-Purcell basin may have ponded against the St. Mary–Laptev transform transfer zone.

Although the Udzha trough strata and other Riphean strata of northern Siberia are remote and poorly exposed, they could provide significant data for testing of the proposed reconstruction. Of particular value would be precise U–Pb ages for tuffs and flows or sills in the Unguokhtakh Formation of the Udzha trough section, as well as the sedimentology and detrital zircon geochronology of terrigenous sedimentary rocks in the Khapchanyr and Udzha formations of the Udzha trough section. These rocks may represent the deposits of distributary influx channels for the postulated Belt-Purcell delta. More U–Pb dates from the Anabar dyke swarms and mafic sills on the west flank of the Anabar massif would be helpful. Similar data also are needed from the Taimyr trough sections. Ideally, similar field and laboratory measurements and lab tests would be obtained from rocks on each craton to establish a more fully compatible data base.

We conclude that the Siberia–west Laurentia connection provides a predictive framework for reconstruction of a hypothetical Belt-Purcell–Udzha basin. We hope that the model stimulates further international collaborative research.

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