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Notes

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ABSTRACT

A non–North American provenance for the lower Belt Supergroup of North America has been used to support various pre-Rodinian paleogeographic reconstructions. Unlike the lower Belt Supergroup, most upper Belt Supergroup provenance studies have inferred Laurentian sediment sources. We test this hypothesis by analyzing U-Pb and Lu-Hf isotopes on detrital zircons, and whole-rock Nd isotopes from the Missoula (upper Belt Supergroup) and Lemhi Groups, and comparing to possible Laurentian sources. Detrital zircons from 11 sandstones analyzed show dominant ages between 1680 and 1820 Ma. These zircons are predominantly magmatic in paragenesis. Belt Supergroup–aged (1400–1470 Ma) and 2400–2700 Ma populations represent minor components. Lu-Hf isotopic analyses for 1675–1780 Ma Missoula Group and Lemhi Group detrital zircons range from εHf(i) +9 to –12 and +8 and –7, respectively. Belt Supergroup–aged grains from the Bonner Formation, Missoula Group, have εHf(i) values between +5 and –9, exceeding coeval ranges from the Mojave and Yavapai terranes [εHf(i) between +5 and 0]. Whole-rock Nd isotopes from Lemhi Group argillites yield a range in εNd(1400) between +1.1 and –5.9. Immature feldspathic sediment, nearly unimodal detrital zircon spectra, and dissimilar Belt Supergroup–aged zircon Hf signatures suggest that distal portions of the Yavapai and Mojave terranes intruded by A-type magmas were not the source for the Missoula and Lemhi Groups. Instead, a slightly modified Mesoproterozoic proto-SWEAT (southwestern United States and East Antarctica) model can best account for the sedimentologic and isotopic characteristics of the Missoula and Lemhi Groups. An alternative model with a source from southeastern Siberia and the Okhotsk Massif is less preferred.

INTRODUCTION

Reconstructions of the early Neoproterozoic supercontinent Rodinia remain contentious (e.g., see Li et al., 2008). Models involving western Laurentia commonly invoke the creation of a late Paleoproterozoic proto-Rodinia that persisted until Rodinia breakup (e.g., Sears and Price, 2003; Goodge et al., 2001) to explain the lack of Grenville-aged belts in southwestern Laurentia. Different reconstructions place East Antarctica (Moores, 1991; Goodge et al., 2008), Australia (Blewett et al., 1998), south China (Li et al., 2008), and Siberia (Sears and Price, 2003) off the western margin of Laurentia during deposition of the Belt Supergroup.

The Mesoproterozoic Belt Supergroup (Purcell Supergroup in Canada) is a 15–20-km-thick package of largely siliciclastic strata extending from southwest Montana (United States) to southern British Columbia (Canada) (Fig. 1; Harrison et al., 1974). The Belt Supergroup, composed of the Lower Belt, Ravalli, Piegan, and Missoula Groups, has played an important part in the proto-Rodinia debate. The lowest three groups, deposited between ca. 1454 and 1470 Ma (Sears et al., 1998; Evans et al., 2000), contain 1570–1590 Ma detrital zircon populations (Ross and Villeneuve, 2003; Link et al., 2007). This age is found in felsic intrusive rocks of the Priest River Complex of Washington and Idaho (Doughty et al., 1998), but is otherwise absent in western Laurentia (Ross and Villeneuve, 2003). The presence of significant 1570–1590 Ma detrital zircons in the Belt Supergroup, combined with an inferred western provenance from paleocurrents (Cressman, 1989), suggests that the continent off Laurentia's western margin included crystalline rocks of that age. The 1570–1590 Ma magmatic rocks in South Australia (Goodge et al., 2008) and north Queensland (Sears and Price, 2003; Blewett et al., 1998) support various Laurentian connections with Australia.

The bulk of the Missoula Group was deposited between 1454 ± 9 and 1401 ± 6 Ma (Evans et al., 2000). Previous provenance studies using detrital zircon and monazite found dominate ages between 1640 and 1860 Ma (Ross et al., 1991; Ross and Villeneuve, 2003). These ages are common in the Mojave and Yavapai provinces of the southwestern United States. Provenance ages combined with northeast-directed paleoflow (Winston, 1986) led most workers to infer a southwest Laurentian source for the Missoula Group, as contrasted with a non-Laurentian, 1570–1590 Ma source for the Lower Belt (Ross and Villeneuve, 2003).

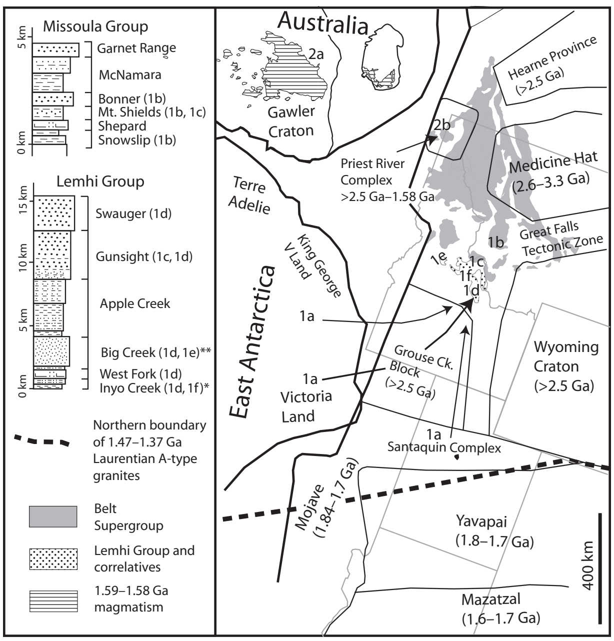

Figure 1. Paleogeographic reconstruction, modified from Goodge et al. (2008). Tie points: 1a—Proposed Antarctic and Laurentian ca. 1.7 Ga crystalline sources for Missoula (1b, 1c) and Lemhi Group (1c, 1d, 1e, 1f) samples. 2a—1590 Ma Gawler Range Volcanics. 2b—1580 Ma felsic augen gneiss (Doughty et al., 1998) from Priest River Complex. Figure is compiled from Goodge et al. (2008), Winston (1986), Foster et al. (2006), Bennett and DePaolo (1987), and Fanning et al. (1988). *1f is from Yellowjacket Formation, correlated to Inyo Creek Formation, and West Fork Formation (Winston et al., 1999). **1e is from Hoodoo Quartzite, correlated to Big Creek Formation (Winston et al., 1999).

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The Lemhi Group is an ~15-km-thick package of largely siliciclastic Mesoproterozoic strata found in east-central Idaho (Fig. 1; Ruppel, 1975). Detrital zircon age spectra from the Lemhi Group match those of the Missoula Group (Link et al., 2007). Detrital zircons (Link et al., 2007) and crosscutting intrusions (Doughty and Chamberlain, 1996) bracket Lemhi Group deposition between 1454 ± 9 Ma and 1370 Ma.

It is widely recognized that Lu-Hf isotope ratios on dated detrital zircons can be used as a geochemical tracer in provenance studies (e.g., see Kinny and Maas, 2003). For this reason, Lu-Hf isotopic analyses were made on dated Paleoproterozoic and Mesoproterozoic detrital zircons from the Missoula and Lemhi Groups. Values for Mesoproterozoic grains are compared with those of A-type granites from southwest Laurentia (Goodge and Vervoort, 2006). A comparison is reasonable because voluminous A-type magmas began intruding much of the Mojave and Yavapai terranes (Fig. 1) ca. 1475 Ma, ~20 m.y. prior to the beginning of Missoula Group deposition, and ~75 m.y. prior to Bonner Formation deposition. We also compare new whole-rock Nd isotope values from fine-grained Lemhi Group strata to possible southwest Laurentian sources (e.g., Bennett and DePaolo, 1987).

METHODS

Detrital zircons were separated from samples of fine- and medium-grained quartzites. Formations sampled and their locations are shown in Figure 1. Zircons from nine samples (see Table DR2 in the GSA Data Repository[1]) were analyzed by a laser ablation–multicollector inductively coupled plasma–mass spectrometer (LA-MC-ICP-MS) at the University of Arizona using techniques outlined in Gehrels et al. (2008). Samples from the Gunsight Formation (49ES08; location 1c in Fig. 1) and the Mount Shields Formation (37ES08; location 1c in Fig. 1) were reanalyzed on the sensitive high-resolution ion microprobe (SHRIMP RG) at the Australian National University. SHRIMP analytical methods were described by Williams (1998). SHRIMP data were reduced using the SQUID Excel macro (Ludwig, 2001) and all isotope plots prepared using Isoplot/Ex 3.00 (Ludwig, 2003). The SHRIMP analysis pits are ~1–2 µm depth × 20 µm diameter, enabling LA-MC-ICP-MS Lu-Hf analyses to be carried out on exactly the same location used for the age determinations. The LA-MC-ICP-MS methods used are similar to those in Munizaga et al. (2008). For the Gunsight and Mount Shields samples, new grain mounts were prepared from another aliquot of the same zircon separate analyzed previously in Arizona. Additional detrital zircon SHRIMP U-Pb ages and Hf isotope ratios were determined for the Bonner Formation and an additional sample of the Mount Shields Formation (both location 1b in Fig. 1). Cathodoluminescence (CL) images were used to identify magmatically zoned zircon grains between 1675 and 1780 Ma and younger than 1470 Ma for the Lu-Hf analysis. Hf analysis was also conducted on dated SHRIMP spots from two detrital zircon samples from Link et al. (2007; 13PL01—Yellowjacket Formation and 02RL888—Hoodoo Quartzite).

Sm-Nd analyses on argillite samples from the Lemhi Group and correlative strata plus one argillite sample from the Missoula Group were performed at the University of Wyoming following protocols described in Frost et al. (2006). For data tables (U-Pb, Lu-Hf, and Sm-Nd) and Universal Transverse Mercator sample locations, see the Data Repository.

[1]GSA Data Repository item 2010257, sample locations; U-Pb, Lu-Hf, and Sm-Nd data; and point count results, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

RESULTS AND DISCUSSION

LA-MC-ICP-MS and SHRIMP U-Pb detrital zircon age spectra from 980 zircon grains in 11 samples from the Mesoproterozoic Missoula and Lemhi Groups, sampled over tens of kilometers of stratigraphy and over hundreds of square kilometers, reveal dominant ages between 1680 and 1820 Ma. The zircons are predominantly zoned igneous grains as determined by CL images. Belt Supergroup–aged (ca. 1400–1470 Ma) grains represent only 4% of all grains, and 2400–2700 Ma zircons represent only 7%. A consistent age distribution is found in every formation sampled and a combined histogram is given in Figure 2 (for individual spectra, see the Data Repository).

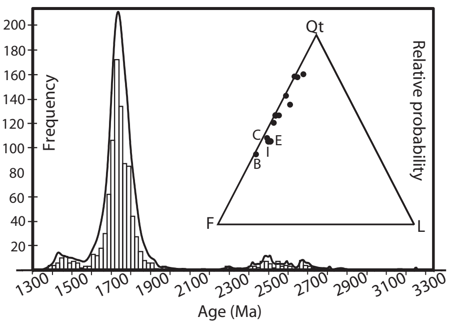

Figure 2. Composite detrital zircon U-Pb age spectrum for 980 zircons from 11 samples of Missoula and Lemhi Groups. Inset is quartz$_{total}$-feldspar-lithic (Qt-F-L) ternary plot for Missoula Group and Lemhi Group detrital zircon samples. For point count data, see the Data Repository (see footnote 1). B—West Fork Formation; C—Big Creek Formation; E—Gunsight Formation; I—Mount Shields Formation.

Hf isotopes from Missoula Group detrital zircons dated between 1675 and 1780 Ma yield a wide range in initial ratios, εHf(i) between +9 and −12 (Fig. 3). The εHf(i) values for 1675–1780 Ma detrital zircons from the Lemhi Group are similar, ranging between +8 and −7. An isotopically heterogeneous source is inferred, ranging from Paleoproterozoic depleted mantle (highest values) to recycled Archean basement (lowest values), and/or mixtures thereof.

Initial Hf isotope values for Belt Supergroup–aged zircons of the Bonner Formation, Missoula Group, yield εHf(i) values between +5 and −9. This range is far greater than the +7–0 εHf(i) range for A-type magmatic zircons from southwest and central Laurentia (Goodge and Vervoort, 2006) (Fig. 3). While three of eight Belt Supergroup–aged Bonner Formation zircons overlap with the εHf(i) range reported by Goodge and Vervoort (2006), the other five have significantly enriched εHf(i) values, indicating derivation from significantly older crust. Southwest Laurentian A-type granites also have high zircon fertility (Dickinson, 2008). Thus the very small number of 1400–1470 Ma zircon grains in the Missoula and Lemhi Groups, combined with different εHf(i) ranges, suggests that the sediment in the Missoula and Lemhi Groups was not sourced from portions of the Mojave and Yavapai terranes intruded by A-type magmas. These zircons may have come from rift-related magmatism in the Belt basin (Evans et al., 2000).

Whole-rock Nd results show significant scatter (Fig. 4), paralleling Hf results. The Gunsight and West Fork Formation samples vary significantly (Gunsight εNd [1400 Ma] of +1.1; West Fork εNd [1400 Ma] of –5.9), despite indistinguishable detrital zircon spectra. The range in εNd is far greater than is recorded in the Mojave and Yavapai provinces (Fig. 4; Bennett and DePaolo, 1987) except for a small portion of the southern Mojave terrane near Death Valley, California, that includes εNd (1400) as low as –9.1 (recalculated to 1400 Ma from Ramo and Calzia, 1998). Despite the low Nd values, Death Valley is an unlikely source for the West Fork Formation. A 500 grain point count of the West Fork revealed slightly >60% feldspar (Fig. 2), suggesting a much more proximal source. In the northern Mojave terrane, the Santaquin Complex of central Utah (Fig. 1) has significantly more juvenile εNd (1400 Ma) values, ranging from +3.8 to –2.5 (recalculated from Nelson et al., 2002).

Our new bulk-rock Nd and zircon Hf isotopic data from Missoula Group and Lemhi Group strata suggest dominant sediment derivation from an isotopically heterogeneous 1680–1820 Ma source, in accord with Ross et al. (1991). This source is likely to have been proximal: arkosic conglomerates of the Bonner

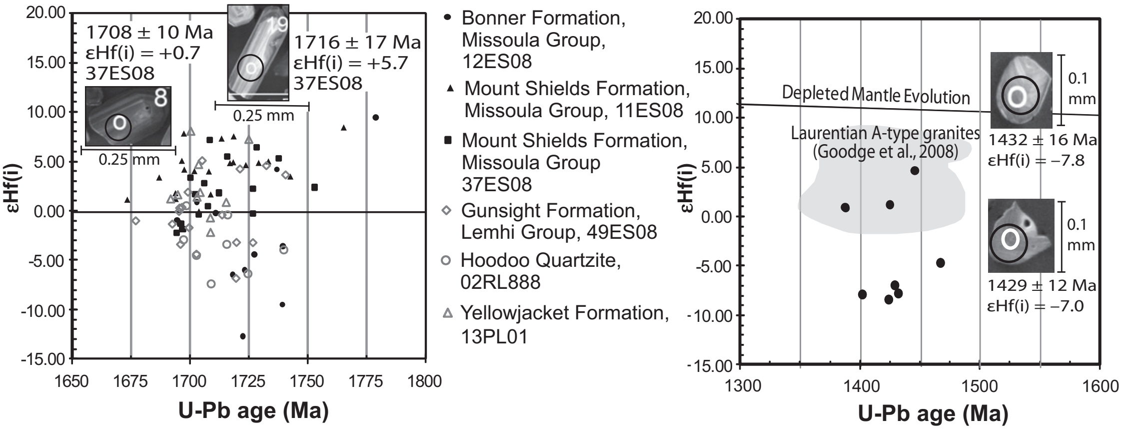

Figure 3. εHf(i) versus U-Pb age for Missoula Group and Lemhi Group zircons. Paleoproterozoic Missoula and Lemhi Group zircons are plotted on left, and Mesoproterozoic zircons from Bonner Formation (Missoula Group) are plotted on right, relative to A-type magmatic zircons from southwest and central Laurentia (Goodge and Vervoort, 2006).

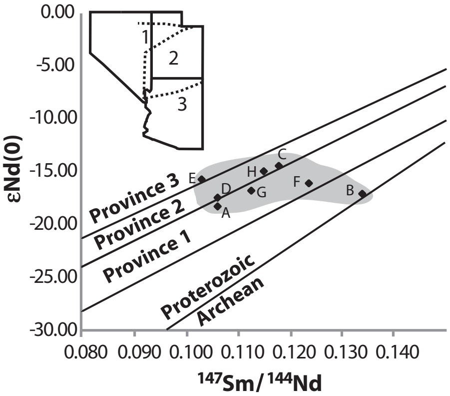

Figure 4. εNd(0) versus $^{147}Sm/^{144}Nd$ for five bulk rock samples from Lemhi Group and three samples from Missoula Group. A—Yellowjacket Formation, B—West Fork Formation, C—Big Creek Formation, D—type Gunsight Formation (location 1d in Fig. 1), E—Gunsight Formation (location 1c in Fig. 1), F—Mount Shields Formation, G—Mount Shields Formation from Frost and Winston (1987), H—Snowslip Formation from Frost and Winston (1987). Province boundaries are from Bennett and DePaolo (1987).

Formation from the Pioneer Mountains, southwestern Montana, contain abundant angular potassium feldspar grains as long as 3 cm. Point counts (n = 500) for Missoula Group and Lemhi Group formations plotted on a quartz-feldspar-lithic ternary diagram (Fig. 2) also suggest a proximal source; three formations have >50% feldspar (Gunsight, Big Creek, and Mount Shields) and one formation has >60% feldspar (West Fork). A nearby Paleoproterozoic magmatic arc developed within Archean crust could produce the observed distribution of age, isotopic, and sedimentologic characteristics. Our data suggest that the Mojave and Yavapai terranes, at least those portions intruded by 1400–1470 Ma magmas, were not responsible for the bulk of upper Belt Supergroup and Lemhi Group detritus. The northernmost Mojave terrane was not intruded by 1400–1470 Ma magmas, and so may have provided some detritus. However, the northern Mojave terrane lacks the more evolved spread in Nd isotope values found in the Lemhi Group. Thus, an additional source is required.

PALEOGEOGRAPHIC IMPLICATIONS

Peucat et al. (1999) reported 2.6 and 2.8 Ga inherited zircons, 1.73–1.76 Ga magmatism, and 1.69 Ga migmatization in Terre Adelie Land, East Antarctica (Fig. 1). They also reported εNd values on ca. 1.7 Ga basement gneisses that, when recalculated to 1400 Ma, range from −3.5 to −7.1. These values are similar to the more negative εNd values from the Lemhi Group. Sediment mixing between the northern Mojave terrane and basement similar to that found in Terre Adelie could account for the spread in εNd values for the Lemhi and Missoula Groups while maintaining consistent detrital zircon spectra. It is likely that 1.7 Ga crust extends southward from Terre Adelie toward southern Victoria Land and the central Transantarctic Mountains (Goodge et al., 2001). The 1.7 Ga magmatic event in Antarctica may have been part of a larger orogen that included the Gawler craton (Australia) and the Mojave terrane (Goodge et al., 2001). This large proposed orogenic event with accompanying magmatism is a good candidate for the extensive magmatic terrane that fed the upper Belt Supergroup and Lemhi Group.

The paleogeographic fit of Figure 1 is similar to the revised SWEAT model of Goodge et al. (2008), though it shifts the East Antarctic and Australian continents southward relative to Laurentia by several hundred kilometers. It still keeps fundamental ties between the Mojave province and the central Transantarctic Mountains, and the inferred 1370–1475 Ma A-type granite belt of Antarctica (Goodge et al., 2008) with southwest Laurentia. In addition to providing a viable sediment source for the Missoula and Lemhi Groups, it has the advantage of linking 1580 Ma magmatism in the Priest River Complex (Doughty et al., 1998) with the Gawler Range Volcanics of South Australia (Fanning et al., 1988).

Alternatively, sediment could have come from 1.73–1.70 Ga anorogenic magmas that melted Archean basement in the Ulkan Complex and Okhotsk Massif (Khudoley et al., 2007) of Siberia (Sears and Price, 2003) (Fig. 5). Sedimentary characteristics suggesting a proximal source, combined with a lack of 1.85–2.0 Ga detrital zircons, make the Siberian model less preferred. Furthermore, this reconstruction is not considered likely due to the abrupt truncation of the ca. 1.4 Ga Laurentian A-type magmatic belt, and its placement of 1.7 Ga rifting in the Okhotsk Massif (Khudoley et al., 2007) adjacent to coeval orogenesis in southwest Laurentia.

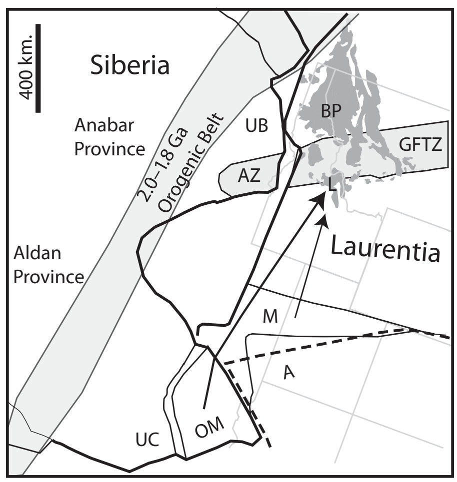

Figure 5. Alternative paleogeographic reconstruction modified from Sears and Price (2003) with possible Belt Supergroup sediment sources including Okhotsk Massif (OM), Ulkan Complex (UC), and Mojave terrane (M). A—1.47–1.37 Ga Laurentian A-type magmatism; boundary is marked by dashed line; BP—Belt-Purcell Supergroup; L—Lemhi Group; UB—Udzha Basin; AZ—Aekit zone; GFTZ—Great Falls Tectonic Zone.

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