Tectonic and sedimentary linkages between the Belt-Purcell basin and southwestern Laurentia during the Mesoproterozoic, ca. 1.60–1.40 Ga

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ABSTRACT

Mesoproterozoic sedimentary basins in western North America provide key constraints on pre-Rodinia craton positions and interactions along the western rifted margin of Laurentia. One such basin, the Belt-Purcell basin, extends from southern Idaho into southern British Columbia and contains a >18-km-thick succession of siliciclastic sediment deposited ca. 1.47–1.40 Ga. The ca. 1.47–1.45 Ga lower part of the succession contains abundant distinctive non-Laurentian 1.61–1.50 Ga detrital zircon populations derived from exotic cratonic sources. Contemporaneous metasedimentary successions in the southwestern United States—the Trampas and Yankee Joe basins in Arizona and New Mexico—also contain abundant 1.61–1.50 Ga detrital zircons. Similarities in depositional age and distinctive non-Laurentian detrital zircon populations suggest that both the Belt-Purcell and southwestern U.S. successions record sedimentary and tectonic linkages between western Laurentia and one or more cratons including North Australia, South Australia, and (or) East Antarctica. At ca. 1.45 Ga, both the Belt-Purcell and southwest U.S. successions underwent major sedimentological changes, with a pronounced shift to Laurentian provenance and the disappearance of 1.61–1.50 Ga detrital zircon. Upper Belt-Purcell strata contain strongly unimodal ca. 1.73 Ga detrital zircon age populations that match the detrital zircon signature of Paleoproterozoic metasedimentary rocks of the Yavapai Province to the south and southeast. We propose that the shift at ca. 1.45 Ga records the onset of orogenesis in southern Laurentia coeval with rifting along its northwestern margin. Bedrock uplift associated with orogenesis and widespread, coeval magmatism caused extensive exhumation and erosion of the Yavapai Province ca. 1.45–1.36 Ga, providing a voluminous and areally extensive sediment source—with suitable zircon ages—during upper Belt deposition. This model provides a comprehensive and integrated view of the Mesoproterozoic tectonic evolution of western Laurentia and its position within the supercontinent Columbia as it evolved into Rodinia.

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INTRODUCTION

Laurentia, the cratonic core of North America (Fig. 1), is a central component in nearly all reconstructions of the supercontinents Rodinia (ca. 1.0 Ga) and Columbia (ca. 1.8 Ga). There is general consensus that northeastern Laurentia was associated with Baltica in both supercontinents (e.g., Zhao et al., 2002; Li et al., 2008; Meert, 2012), and geological correlations suggest that the two cratons were tectonically linked from ca. 1.8 Ga to the breakup of "eastern" Rodinia ca. 0.6 Ga (Gorbatschev and Bogdanova, 1993; Åhäll and Gower, 1997; Karlstrom et al., 2001; Li et al., 2008). Long-lived, subduction-related growth ca. 1.8–1.3 Ga formed a magmatic accretionary belt that extended across southern Laurentia, Greenland, and Baltica (Zhao et al., 2004, and references therein). In Laurentia, this belt is represented by the ca. 1.78–1.60 Yavapai and Mazatzal Provinces in the central and southwestern United States (Fig. 1; e.g., Whitmeyer and Karlstrom, 2007) and much of the imbricated basement of the Grenville Province in the southern to northeastern United States and eastern Canada (Fig. 1; e.g., Rivers, 1997). These belts and other Precambrian provinces are truncated along the rifted western margin of Laurentia (Fig. 1), and the positions of formerly adjacent cratons to the west (present coordinates) in both Rodinia (e.g., Moores, 1991; Burrett and Berry, 2000; Sears and Price, 2000; Li et al., 2008) and Columbia (e.g., Zhao et al., 2004; Payne et al., 2009; Evans and Mitchell, 2011; Meert, 2012) are widely debated. Additional constraints are needed for supercontinent reconstructions for the period between Columbia assembly ca. 1.8 Ga and Rodinia breakup beginning ca. 0.75 Ga.

In western North America, Mesoproterozoic sedimentary basins provide key constraints on pre-Rodinia craton positions and interactions. One notable example is the Belt-Purcell basin, extending from southern Idaho into British Columbia in western North America (Figs. 1 and 2), which contains a >18-km-thick succession of siliciclastic sediment and minor carbonate layers that accumulated across more than 200,000 km^2 between ca. 1.47 and 1.40 Ga (Fig. 2B, panel B; Winston and Link, 1993; Evans et al., 2000; Lydon, 2000). The Belt-Purcell Supergroup consists of four major groups: the Lower Belt-Purcell, Ravalli, Piegan, and Missoula (Fig. 2B). The discovery of abundant non-Laurentian ca. 1.61–1.50 Ga detrital zircons in the lower three units (see Fig. 2B, panel C; Ross et al., 1992; Ross and Villeneuve, 2003) established Belt-Purcell strata as an important keystone in Mesoproterozoic plate reconstructions. Ca. 1.61–1.50 Ga ages from detrital zircons correspond to a distinctive, globally uncommon age range (Condie et al., 2009). There are few known localities in western Laurentia with ca. 1.60–1.58 Ga igneous rocks, such as the Priest River complex in northern Idaho (PRC in Fig. 2A; Doughty et al., 1998). However, these potential sources are localized and do not match the entire range of observed detrital zircon ages recognized.

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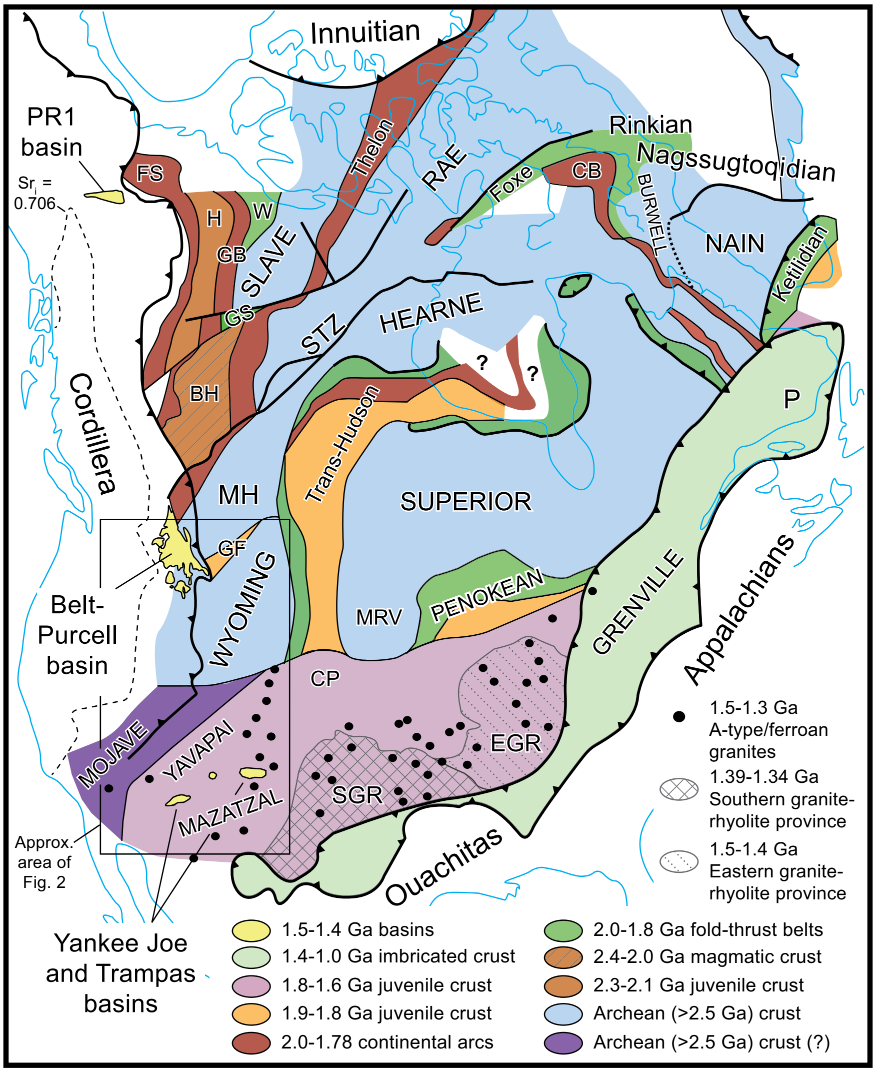

Figure 1. Map showing Precambrian tectonic elements of the Laurentian craton (adapted from Hoffman, 1988; Ross and Villeneuve, 2003; Piercey and Colpron, 2009). Greenland is restored prior to rifting from North America. The line of initial $^{87}Sr/^{86}Sr$ ratios (Sr$_i$) = 0.706 (dashed line in western North America; from Armstrong, 1988) indicates the rifted western margin of the craton. Location and outline of 1.5–1.4 Ga PR1 basin in western Yukon is from Medig et al. (2014); Yankee Joe and Trampas basin outlines are from Doe et al. (2013) and Daniel et al. (2013), respectively. Abbreviations: BH—Buffalo Head terrane; CB—Cumberland batholith; CP—Central Plains orogen; EGR—Eastern Granite-Rhyolite province; FS—Fort Simpson magmatic arc; GB—Great Bear magmatic arc; GF—Great Falls tectonic zone; GS—Great Slave shear zone; H—Hottah terrane; MH—Medicine Hat block; MRV—Minnesota River valley subprovince; P—Pinware terrane; SGR—Southern Granite-Rhyolite province; STZ—Snowbird tectonic zone; W—Wopmay orogen.

Instead, ca. 1.61–1.50 Ga detrital zircons are interpreted to be derived from one or more formerly adjacent cratons such as Australia or Antarctica (Ross and Villeneuve, 2003; Stewart et al., 2010). At around 1.45 Ga, detrital zircons in the uppermost Belt-Purcell strata (i.e., Missoula Group) record a pronounced shift to strongly unimodal populations consistent with southwestern Laurentian sources and possibly additional non-Laurentian provenance. Ca. 1.61–1.50 Ga detrital zircons are notably absent in the Missoula Group and correlative Belt-Purcell strata (Fig. 2B, panel A; Stewart et al., 2010).

Recent work in the southwestern United States, more than 1600 km to the south-southeast of the Belt Supergroup, has revealed multiple metasedimentary successions with depositional ages and provenance patterns that are strikingly similar to the Belt-Purcell strata. These successions include the Yankee Joe Group in central Arizona, quartzite exposed in the Defiance uplift in northeastern Arizona, and the Trampas Group in northern New Mexico (Fig. 2A; Daniel et al., 2013; Doe et al., 2013). These siliciclastic successions are up to 1.5 km or more thick as presently exposed, and all contain abundant 1.61–1.50 Ga detrital zircon. Like the Belt-Purcell strata, successions in northern New Mexico record a pronounced shift in provenance ca. 1.45 Ga from non-Laurentian to local sources. Whereas the Belt-Purcell basin remained largely undeformed until at least ca. 1.37 Ga (Doughty and Chamberlain, 1996), successions in southwestern Laurentia underwent regional orogenesis—the Picuris orogeny (Daniel et al., 2013). The onset of regional orogenesis to the southwest ca. 1.45 Ga is, in part, recorded by the major shift in sediment provenance. This collisional event buried the southwest successions to midcrustal depths, propagated deformation throughout Proterozoic crustal domains to the northwest, and likely shed voluminous amounts of sediment northward into the Belt-Purcell basin (Daniel et al., 2013; Doe et al., 2013).

In this paper, we synthesize published detrital zircon data from Paleoproterozoic and Mesoproterozoic metasedimentary successions exposed throughout western Laurentia that illustrate key similarities and differences between the Belt-Purcell basin and the contemporaneous metasedimentary successions in the southwestern United States. We highlight the presence of distinctive non-Laurentian detrital zircon populations in coeval basins spanning more than 3500 km of the Mesoproterozoic western Laurentian margin and discuss their significance in terms of the configuration and evolution of the supercontinent Columbia. We present a tectonic model in which basins were linked with sediment sources from Australia and (or) Antarctica ca. 1.48–1.45 Ga prior to removal of the non-Laurentian sources by rifting. Beginning ca. 1.45 Ga, basins in the southwestern United States were buried by a regional fold-and-thrust belt, and synorogenic conglomerates were derived from local exhumed basement sources. At the same time, sediment in the upper Belt strata was largely derived from orogenic unroofing of the foreland region, mostly comprising the 1.78–1.70 Ga Yavapai Province, beginning 1.45 Ga, with supporting evidence from detrital zircon age distributions, regional depth of Proterozoic exposure, and published thermochronology. Our proposed scenario raises numerous testable hypotheses for broadly integrating the Mesoproterozoic tectonic evolution of western Laurentia with key implications for pre-Rodinia plate configurations during the transition from Columbia to Rodinia.

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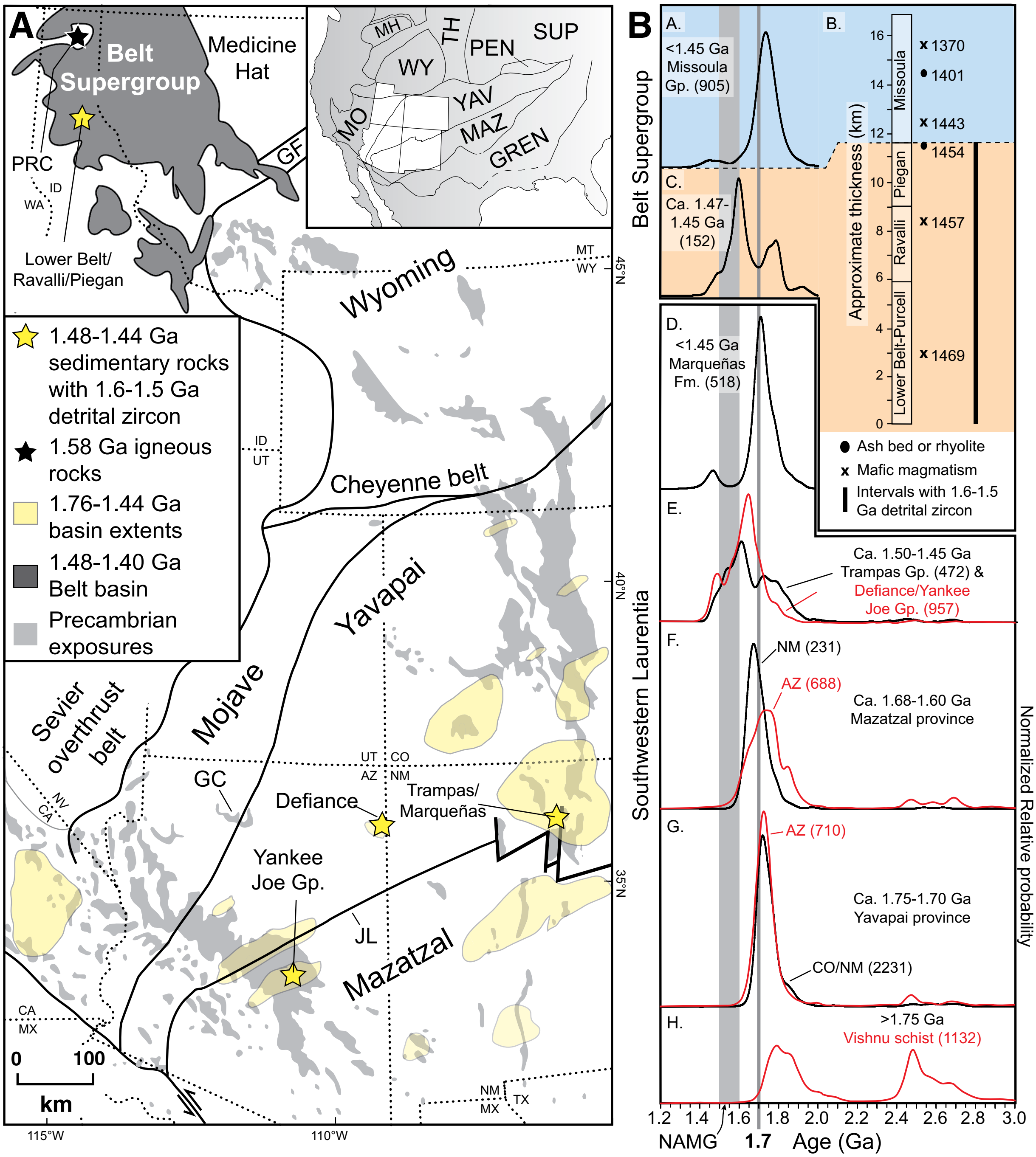

Figure 2. (A) Map showing Precambrian provinces (separated by solid lines) and rock exposures (light-gray shapes) in the western United States. Areas outlined in yellow show inferred extent of Paleoproterozoic and Mesoproterozoic sedimentary basins, and stars highlight localities discussed in the text. PRC—Priest River complex; GF—Great Falls tectonic zone; GC—Grand Canyon; JL—Jemez/Morenci Lineament; TG/MQ—Trampas Group and Marqueñas Formation. Inset shows: MH—Medicine Hat block; MO—Mojave; WY—Wyoming; TH—Trans-Hudson; PEN—Penokean; SUP—Superior; YAV—Yavapai; MAZ—Mazatzal; GREN—Grenville. (B) Compiled detrital zircon geochronologic data for the lower three units (orange, panel C) and upper unit (blue, panel A) of the Belt-Purcell Supergroup together with generalized stratigraphy and published depositional age constraints (panel B; Doughty and Chamberlain, 1996; Doughty et al., 1998; Sears et al., 1998; Evans et al., 2000; Ross and Villeneuve, 2003; Lewis et al., 2006; Link et al., 2007, 2013; Stewart et al., 2010). (C) Compiled detrital zircon geochronologic data and likely depositional age ranges from 1.75 to 1.45 Ga metasedimentary successions exposed in the southwestern United States; red probability density curve and labels indicate Arizona (AZ) localities, and black curves and labels indicate Colorado and/or New Mexico (CO/NM) localities (Jessup et al., 2005; Jones and Connelly, 2006; Amato et al., 2008; Jones et al., 2009, 2011; Shufeldt et al., 2010; Doe et al., 2012, 2013; Jones and Thrane, 2012; Daniel et al., 2013; Doe, 2014). Numbers in parentheses for detrital zircon age spectra indicate number of grains included in each age probability density curve. Note that the detrital zircon age spectra are all composites of multiple samples from previously published data sets referenced above, and the composite curves might mask statistically significant age populations from individual samples. NAMG—North American magmatic gap.

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EVOLUTION AND PROVENANCE OF THE BELT-PURCELL SUPERGROUP

The Belt-Purcell Supergroup is generally divided into four major units: the Lower Belt-Purcell, Ravalli, Piegan, and Missoula Groups (Fig. 2B, panel B). With the exception of parts of the Lower Belt Group, most units are interpreted as continental and shallow-water deposits, although the question of marine versus nonmarine deposition is still debated (e.g., Winston and Link, 1993; Frank et al., 1997). The basin formed in a complex intracontinental rift system containing variable sediment thicknesses, depositional environments, and sedimentary facies distributions. Age control from interlayered rhyolite and tuff and crosscutting mafic intrusive rocks indicates that initial rifting, basin formation, and most of the sediment accumulation occurred between ca. 1.47 Ga and ca. 1.40 Ga (Fig. 2B, panel B; Anderson and Davis, 1995; Doughty and Chamberlain, 1996; Sears et al., 1998; Evans et al., 2000).

Strata within the lower three groups (Lower Belt-Purcell, Ravalli, and Piegan Groups; Fig. 2B, panel B) have complex, multimodal detrital zircon populations that reflect Laurentian sources in the eastern part of the basin, with prominent age groupings around 2.60 Ga and 1.80 Ga (Ross and Villeneuve, 2003). In the western part of the basin, these same units are characterized by 1.92–1.46 Ga detrital zircon ages, with abundant grains having distinctive ages between ca. 1.61 and 1.50 Ga (Fig. 2B, panel C; Ross and Villeneuve, 2003; Link et al., 2007). This age range is uncommon globally (Condie et al., 2009; Voice et al., 2011) and corresponds with the North American magmatic gap (NAMG in Fig. 2), a time period generally interpreted to represent tectonic quiescence in western Laurentia. There are a few exceptions, including ca. 1.58 Ga orthogneiss in the Priest River complex in northern Idaho, which is adjacent to the western Belt basin (PRC in Fig. 2A; Doughty et al., 1998), and ca. 1.60–1.59 Ga volcanic rocks and diabase in northwestern Canada (Wernecke breccia and Western Channel diabase; Thorkelson et al., 2001; Hamilton and Buchan, 2010). However, the age range of these few known western Laurentia localities is too restricted to account for detrital zircon ages 1.58 Ga and younger in lower Belt strata (Fig. 2B, panel C). Paleocurrent data in the lower Belt strata indicate a western sediment source (present coordinates) across the rifted Laurentian margin (Figs. 1 and 2; Winston et al., 1989; Ross and Villeneuve, 2003), and Australia is perhaps the only known continent with an established record of magmatic activity and tectonism spanning the entire 1.61–1.50 Ga range of detrital zircon ages (Betts and Giles, 2006; Condie et al., 2009); thus, Ross and Villeneuve (2003) suggested Australia as the most likely source for non-Laurentian detrital zircon in the lower two thirds of the Belt Supergroup.

The Missoula Group in upper Belt strata (Fig. 2B, panel B) records the sedimentological effects of basin reorganization. The transition is also marked by mafic magmatism, faulting within the basin, the reappearance of coarse clastic material including abundant feldspathic detritus, a shift to north-directed paleocurrents, an absence of 1.61–1.50 Ga detrital zircons, and detrital zircon age populations more consistent with derivation from Paleoproterozoic and Archean provinces to the east and southeast (Fig. 1; Winston, 1986; Ross and Villeneuve, 2003; Stewart et al., 2010). Missoula Group strata have an average total thickness of ~5 km, and correlative sections such as Lemhi Group are locally up to 15 km thick (Link et al., 2007; Stewart et al., 2010). Detrital zircon age populations throughout the entire section are predominately Paleoproterozoic and strongly unimodal, with a prominent ca. 1.73 Ga age population (Fig. 2B, panel A; Stewart et al., 2010; Link et al., 2013). Limited Hf data from detrital zircons and Nd data from argillites within the upper Belt strata indicate isotopic heterogeneity in the Paleoproterozoic source region(s), leading Stewart et al. (2010) to suggest East Antarctica as the primary sediment source for upper Belt strata.

Magmatism, metamorphism, and deformation associated with the ca. 1.38–1.30 Ga East Kootenay orogeny affected parts of the Belt-Purcell basin, possibly overlapping with the end of and/or terminating deposition (McMechan and Price, 1982; Doughty and Chamberlain, 1996; Zirakparvar et al., 2010). Otherwise, basin strata were not pervasively deformed and metamorphosed during the Mesoproterozoic.

EVOLUTION AND PROVENANCE OF SOUTHWESTERN LAURENTIA METASEDIMENTARY SUCCESSIONS

Thick, ca. 1.75–1.45 Ga metasedimentary successions exposed throughout the southern Rocky Mountains and southwestern United States (Fig. 2A) represent repeated cycles of sedimentation associated with prolonged accretionary orogenesis that propagated southward from the southern margin of the Archean Wyoming Province (Amato et al., 2008; Jones et al., 2009, 2011; Jones and Thrane, 2012).

Paleoproterozoic successions in Colorado and New Mexico have strongly unimodal detrital zircon age spectra that largely reflect local sources (Fig. 2B, panels F and G). The ca. 1.75 Ga Vishnu Schist, exposed primarily in the Grand Canyon of Arizona (GC in Fig. 2A), is a notable exception that contains a bimodal detrital zircon age distribution interpreted to reflect a mixture of local and non-Laurentian Archean sources (Fig. 2B, panel H; Shufeldt et al., 2010). Ca. 1.68–1.60 Ga metasedimentary rocks in Arizona are another exception because they also show evidence for reworking of older basement sources (Fig. 2B, panel F; Doe et al., 2012; Doe, 2014), possibly including the Vishnu Schist. Throughout the U.S. Southwest, Paleoproterozoic metasedimentary successions show evidence of polyphase deformation and associated metamorphism. In Colorado, Paleoproterozoic metasedimentary successions are commonly exposed as tight synclinal keels surrounded by deeply exhumed metamorphosed basement rocks and granitoids (Jones et al., 2009). In New Mexico and Arizona, successions are part of regional fold-and-thrust systems (Williams, 1991; Karlstrom and Daniel, 1993; Doe et al., 2012) and were metamorphosed at greenschist to upper-amphibolite facies. Deformation and metamorphism likely represent both Paleoproterozoic and Mesoproterozoic orogenic events, although evidence for Paleoproterozoic events is commonly obscured by the pervasive effects of ca. 1.45 Ga orogenesis (Daniel and Pyle, 2006; Daniel et al., 2013).

Multiple successions of metasedimentary rocks exposed in Arizona and New Mexico previously thought to be Paleoproterozoic are now known to be Mesoproterozoic (e.g., Jones et al., 2011; Doe et al., 2012), leading to new insights into the extent and influence of Mesoproterozoic orogenesis in the U.S. Southwest. These successions, including the Yankee Joe Group, quartzite exposed along the Defiance uplift, and the Piedra Lumbre Formation of the Trampas Group (for locations, see Fig. 2A), yield complex detrital zircon age spectra with grains as young as 1.46 Ga and an abundance of non-Laurentian 1.61–1.49 Ga age populations (Fig. 2B, panel E; Doe et al., 2012, 2013; Daniel et al., 2013). The Pilar Formation, which underlies the Piedra Lumbre Formation, also contains interbedded metatuff layers with zircon ages of 1.49 Ga (Daniel et al., 2013). Metatuff layers are also recognized in the Yankee Joe Group, and preliminary ages suggest that they are ca. 1.50–1.48 Ga (Bristol et al., 2014). These metasedimentary successions are up to 1.5 km thick and overlie many kilometers of Paleoproterozoic metasedimentary and metavolcanic rocks. In both Arizona and New Mexico, there is no evidence for an angular unconformity between the Paleoproterozoic and Mesoproterozoic successions. The detrital zircon characteristics of these successions are remarkably similar, and depositional ages are generally constrained between

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ca. 1.50 and 1.44 Ga (Doe et al., 2012; Daniel et al., 2013). The three exposure areas (marked by yellow stars in Fig. 2A and inferred basin extents in Fig. 3A) trend northeast parallel to the Jemez lineament (JL in Fig. 2A), one candidate for a possible Proterozoic crustal suture zone between the Yavapai and Mazatzal crustal provinces (Karlstrom and Humphreys, 1998). This alignment, shown schematically in Figure 3A, suggests that separate, contemporaneous basins might have formed along a major regional structural feature such as an aulacogen or foreland basin system formed during ca. 1.49–1.45 Ga convergence (Daniel et al., 2013).

The Marqueñas Formation, exposed within a few kilometers of the Trampas Group in the Picuris Mountains of northern New Mexico (Fig. 2), records the onset of orogenesis ca. 1.45 Ga. Unlike the 1.48–1.44 Ga successions, the Marqueñas Formation contains no 1.61–1.49 Ga detrital zircons and, instead, yields strongly unimodal detrital zircon age spectra representing local ca. 1.71 Ga sources and subsidiary ca. 1.45 Ga populations (Fig. 2B, panel D). Boulder to pebble conglomerate and quartzite of the ~500-m-thick unit are interpreted to represent a broad alluvial fan shed off a northward-propagating orogen formed along the Yavapai-Mazatzal boundary. The overlap between deposition of the Marqueñas Formation and metamorphic mineral ages in the older successions is consistent with a history of 1.48–1.44 Ga deposition closely followed by thrust burial, ductile deformation, and regional metamorphism associated with the Picuris orogeny (Daniel et al., 2013).

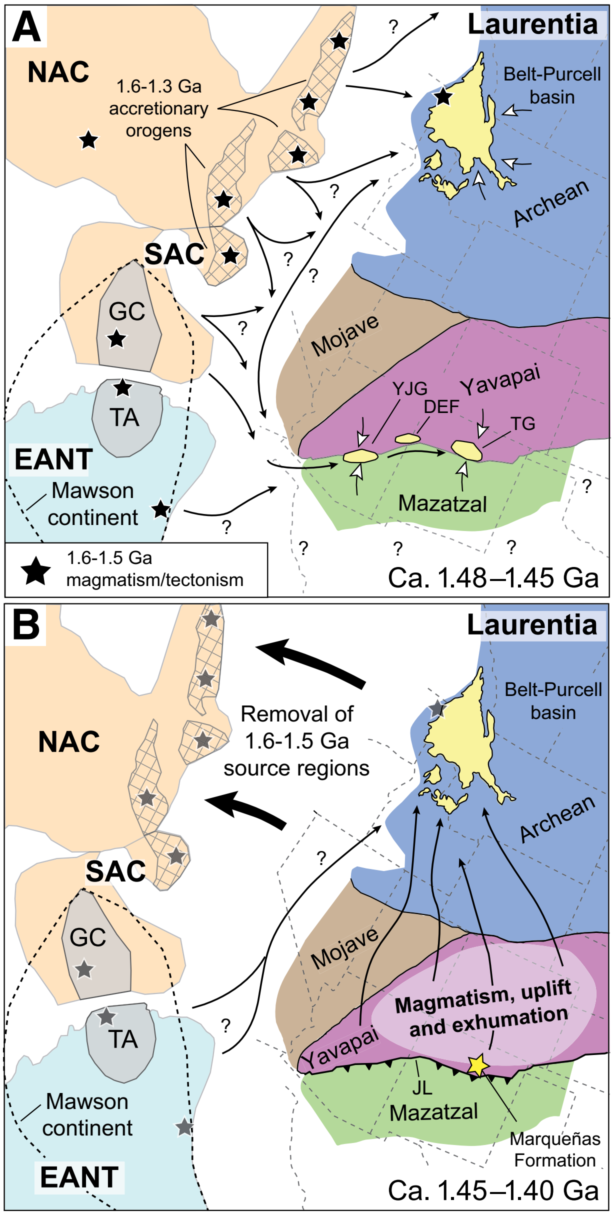

Figure 3. Speculative paleogeographic reconstructions showing possible sedimentary connections between non-Laurentian sources, the Belt-Purcell basin, and the Yankee Joe Group (YJG), Defiance quartzite (DEF), and Trampas Group (TG) basins in the southwestern United States. Position of western cratons is after Doe et al. (2012). (A) Candidate source regions from the North Australia craton (NAC), South Australia craton (SAC), and East Antarctica (EANT) together with hypothetical sediment pathways on the basis of provenance patterns discussed in the text. (B) Removal of 1.61–1.50 Ga sources beginning 1.45 Ga by rifting of western craton(s) at the same time as regional orogenesis in southern Laurentia along the Yavapai-Mazatzal boundary (approximated by the Jemez lineament [JL]). GC—Gawler craton; TA—Terre Adelie craton.

MESOPROTEROZOIC TECTONIC AND SEDIMENTOLOGICAL LINKAGES IN WESTERN LAURENTIA AND REGIONAL TO GLOBAL IMPLICATIONS

The similarity between depositional ages and provenance patterns between the Belt-Purcell basin and coeval southwestern Laurentia successions, particularly the abundance and subsequent disappearance of distinctive 1.61–1.50 Ga detrital zircons, is undeniable. This similarity suggests that the two depositional systems evolved within the same broad tectonic setting on the western margin of Laurentia, and they shared sources of exotically derived detrital zircons. Both Mesoproterozoic sedimentary systems provide key constraints for determining the relative position of cratons within the Columbia supercontinent, with one possibility illustrated in Figure 3. The South Australia craton and large parts of East Antarctica are geologically linked within the reconstructed Mawson continent ca. 1.73–1.55 Ga (schematic outline shown with dashed line in Fig. 3; Payne et al., 2009), and Payne et al. (2009) suggested that the Mawson continent and North Australia craton were contiguous throughout the Paleoproterozoic. The plate reconstruction in Figure 3A shows one possible geometry of these cratons relative to western Laurentia (after Doe et al., 2012) and highlights the abundance of suitable source regions in the northern and southern Australia cratons (NAC and SAC in Fig. 3) and, to a lesser extent as presently known, in East Antarctica (EANT in Fig. 3).

In our preferred interpretation, ca. 1.48–1.44 Ga metasedimentary successions in southwestern Laurentia formed along a northeast-striking basin network parallel to and inboard of the southwestern Laurentian margin. Supply of non-Laurentian sediment containing 1.61–1.50 Ga detrital zircons was likely from the southwest (present coordinates), although supporting paleocurrent data are largely absent in the deformed and metamorphosed successions. The sediment supply systems were linked with the Belt-Purcell rift basin along the western Laurentian margin, allowing sediment mixing from different source regions. The recent discovery of metasedimentary rocks in western Yukon Territory, Canada, with abundant 1.50 Ga detrital zircons raises the possibility that contemporaneous basinal strata with non-Laurentian provenance extend from as far north as Yukon (PR1 basin in Fig. 1) to as far south as Arizona (Medig et

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al., 2014). We also acknowledge the uncertainty in crossing sediment pathways shown in Figure 3A, but available detrital zircon data indicate an apparent paradox. Successions to the north (Yukon) and south (Arizona and New Mexico) contain significant numbers of grains with ages of ca. 1.56–1.49 Ga, which are more consistent with the known geological record of the North Australian craton (Doe et al., 2012, 2013; Medig et al., 2014). In contrast, lower Belt strata are dominated by 1.59 Ga detrital zircon, suggesting a strong association with the South Australia craton and East Antarctica components of the Mawson continent (Ross and Villeneuve, 2003; Link et al., 2007). Detrital zircon data from the respective Australian cratons show similar patterns, with sediment derived from the Gawler region of the South Australia craton having a prominent ca. 1.59 Ga population (Belousova et al., 2009) and sediment derived from the Mount Isa district of the North Australia craton containing more diverse 1.61–1.50 Ga ages, including populations at ca. 1.57, 1.52, and 1.51 Ga (Griffin et al., 2006). Potential bedrock source regions in Australia are very well characterized for Hf, and studies that carefully integrate U-Pb, Lu-Hf, and other isotopic constraints on metasedimentary rocks are able to resolve specific source regions within the continent (e.g., Griffin et al., 2006; Belousova et al., 2009; Howard et al., 2009, 2011). However, these types of studies have not yet been systematically carried out in the western Laurentia basins described herein, but such studies are ultimately expected to provide the key insights to address the uncertainties about sediment sources.

By ca. 1.45 Ga, ca. 1.61–1.50 Ga detrital zircons are absent in western North America, signaling the removal of non-Laurentian source regions of this age. This evolving source configuration is shown schematically in Figure 3B and is supported by paleomagnetic data indicating separation of Australia and Laurentia after ca. 1.55 Ga but well before ca. 1.20 Ga (Pisarevsky et al., 2014). The prevalence of unimodal 1.73 Ga populations throughout many kilometers of upper Belt strata over a vast area suggests a very large source region with a relatively consistent zircon age signature (Fig. 2B, panel A; e.g., Link et al., 2013). Winston (1986) noted a change to northwestward paleoflow directions in the Missoula Group consistent with a shift to southwestern Laurentia as a primary source region. The similarity of detrital zircon age spectra between upper Belt strata and metasedimentary rocks in the Yavapai Province (Fig. 2B, panel G) suggests that the Paleoproterozoic metasedimentary successions were a likely source.

Tightly folded and deeply exhumed roots of these successions throughout the Yavapai Province suggest that areally extensive, thick successions of Paleoproterozoic metasedimentary rocks were uplifted and eroded together with surrounding basement rocks during Mesoproterozoic orogenesis and magmatism. Mesoproterozoic hornblende and mica ^{40}Ar-^{39}Ar ages are widespread throughout the Yavapai Province and generally get younger from north to south (Shaw et al., 1999, 2005). The ubiquity of ca. 1.45 Ga and younger mica cooling ages throughout the Paleoproterozoic province is interpreted to represent a regional thermal event associated with regional 1.47–1.36 Ga magmatism. However, the north to south younging of both hornblende and mica cooling ages (Shaw et al., 2005), together with the increasing degree of preservation of metasedimentary successions to the south, suggests that these ages also represent a major Mesoproterozoic unroofing event within the Yavapai Province. Bedrock uplift and exhumation were likely influenced by both the thermal effects of extensive magmatism and the inboard effects of crustal thickening that propagated into the continent to the northwest (Fig. 3B) during the ca. 1.45–1.40 Ga Picuris orogeny (Daniel et al., 2013). The locus of crustal thickening was broadly centered along the Yavapai-Mazatzal Province boundary in northern New Mexico (approximated by JL in Fig. 3; Karlstrom and Humphreys, 1998; Magnani et al., 2005; Daniel et al., 2013). Extensive exhumation and erosion throughout the Yavapai province ca. 1.45–1.36 Ga would have provided a voluminous and areally extensive potential sediment source throughout the entire time interval of upper Belt deposition. The resulting sediment was rich in 1.73 Ga detrital zircons (Fig. 2B, panel G) and would have been shed northward from a growing orogenic front near the southern Laurentian margin (Daniel et al., 2013; Doe, 2014).

The similarity in the zircon age signature of the Yavapai Province and the Paleoproterozoic detrital zircon age component of the Missoula Group is striking (Fig. 2B, panels A and G). However, unlike the globally uncommon 1.6–1.5 Ga time interval, 1.9–1.7 Ga is a major time of crustal preservation (Voice et al., 2011). Thus, the prominent unimodal 1.73 Ga peaks in the upper Belt strata might not necessarily require a unique source. Available Hf data from detrital zircons and Nd data from upper Belt argillites indicate that sediment was derived from sources with both juvenile and evolved isotopic character (Stewart et al., 2010). Igneous rocks of the Yavapai Province are generally juvenile with respect to both Nd and Hf (Bennett and DePaolo, 1987; Goodge and Vervoort, 2006; Doe, 2014). Limited Hf data suggest the presence of older (>1.8 Ga) crust in certain areas (e.g., Bickford et al., 2008), but the age and extent of these more isotopically evolved components and their influence on the Hf isotopic character of detrital zircon have not been adequately assessed. We suggest that by rifting the western cratons from north to south in our proposed reconstruction (shown schematically in Fig. 3B), candidate sources in East Antarctica could have remained connected to western Laurentia during deposition of the upper Belt strata. These sedimentary supply systems could have also crossed the northwestern Mojave Province, consistent with the preferred model of Stewart et al. (2010), and also mixed with supply systems emerging from the Yavapai Province. More comprehensive Hf isotopic characterization of both detrital zircon and potential bedrock sources—particularly Proterozoic igneous rocks in the western United States—is critical for refining provenance models for these grains, especially considering the global abundance of suitable ages.

More detailed sampling throughout the lower Belt strata will help to further test the presence and abundance of different 1.6–1.5 Ga detrital zircon age populations. In addition, routine measurement of additional isotopic discriminants such as Hf in detrital zircons and in prospective source regions will help to define more specific global sources during this distinctive time period and, together with other key constraints such as paleomagnetic data (e.g., Pisarevsky et al., 2014) and detailed geologic histories, will lead to unique solutions for postulated craton positions and sediment distribution systems. Continued detailed study of candidate source cratons including Laurentia might also reveal ca. 1.6–1.5 Ga zircon sources that are not yet recognized. The few known Laurentian sources, such as the 1.58 Ga components of the Priest River complex (Doughty et al., 1998), also need to be characterized for Hf.

The Mesoproterozoic basins discussed herein preserve one of the few records of continent interactions within part of Columbia. Our proposed linkages between the Belt-Purcell basins and contemporaneous successions in the southwestern United States provide a more integrated view of the Proterozoic tectonic evolution of southern Laurentia in the context of the evolving supercontinent. More extensive sampling investigations throughout the basins combined with comprehensive and systematic isotopic characterization of detrital zircon, metasedimentary rocks, and their prospective bedrock source regions are essential for adequately addressing the remaining uncertainties regarding the provenance, basin evolution, and tectonic interactions between formerly adjacent cratons. Such studies will also lead to a more comprehensive and integrated understanding of the tectonic evolution of North

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America and other connected elements in Proterozoic supercontinent cycles.

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