Paleoproterozoic evolution of the Farmington zone: Implications for terrane accretion in southwestern Laurentia

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ABSTRACT

Precambrian rocks in the Farmington zone in northeastern Utah provide important constraints on the accretionary history of southwestern Laurentia because they lie at the orogenic intersection of the Wyoming, Yavapai-Colorado, and Mojave provinces. Approximately 200 U-Pb analyses of zircons from Paleoproterozoic rocks in the Wasatch Mountains (Farmington Canyon and Little Willow complexes) and Uinta Mountains (Owiyukuts and Red Creek complexes) indicate: (1) U-Pb ages of 2.446 ± 0.011 Ga for igneous zircons from a meta-igneous rock and 2.42 Ga for the youngest detrital zircon from a metasedimentary rock constrain the age of the Farmington Canyon complex and represent a heretofore unreported Paleoproterozoic event in southwestern North America; (2) Most lithologies in all areas are metasupracrustal and U-Pb ages of most detrital zircons and whole-rock Sm-Nd data clearly indicate a primarily Archean provenance for the metasedimentary rocks; and (3) Metamorphism, including partial melting, occurred at 1.674 ± 0.012 Ga (2σ) based on U-Pb ages of 36 of 38 zircons (overgrowths and whole grains with Th/U <0.1) from metamorphic rocks, including leucosomes, from both the Wasatch and Uinta Mountains. These observations combined with previous work suggest a geologic history that begins with development of a Paleoproterozoic passive or rifted margin along the southwestern edge of the Wyoming craton and terminates with Paleoproterozoic accretion of Mojavia (±Yavapai-Colorado) to the Wyoming Province. Crystallization and model ages of the Farmington sequence suggest a possible genetic link between Mojavia, the Farmington zone, and the Wyoming Province, which would provide new constraints on proposed Neoproterozoic conjugates and the role of the Cheyenne belt in the accretionary tectonics of southwestern Laurentia.

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INTRODUCTION

Precambrian rocks from limited exposures in northeastern Utah provide important constraints on the accretionary history of southwestern Laurentia because they lie near a "triple junction" of crustal convergence between the Wyoming, Mojave, and Yavapai-Colorado provinces (the Yavapai and Colorado provinces are considered a single entity in this discussion [e.g., Whitmeyer and Karlstrom, 2007]). This area is also along strike of the Cheyenne belt, which marks the boundary between the Proterozoic Colorado-Yavapai province and the Archean crust of the Wyoming craton in eastern Wyoming (Fig. 1; e.g., Hills and Houston, 1979; Karlstrom and Houston, 1984; Duebendorfer and Houston, 1987; Nelson et al., 2002; Jones et al., 2010). Although the significance of the rocks in northeastern Utah has been recognized for decades, previous attempts to accurately determine their ages and metamorphic history have produced conflicting results and their origin has remained enigmatic (Sears et al., 1982; Hedge et al., 1983; Barnett et al., 1993; Nelson et al., 2002, 2011). In this study, we report ~200 U-Pb analyses obtained using the SHRIMP-RG (Sensitive high-resolution ion microprobe–reverse geometry) of magmatic, metamorphic, and detrital zircons from two Precambrian basement localities in northeastern Utah (Fig. 1): the Wasatch Range (Farmington Canyon and Little Willow complexes) and the eastern Uinta uplift (Owiyukuts complex and Red Creek quartzite); and discuss their significance for the accretion of Proterozoic terranes to southwestern Laurentia.

GEOLOGIC RELATIONS

Farmington Canyon Complex

Bryant (1988) and Yonkee et al. (2000) described the complex as primarily an association of metasupracrustal rocks (schists, gneisses, and quartzites), migmatites grading to quartz monzonite gneiss, and discontinuous mafic bodies and pegmatites metamorphosed to upper amphibolite-granulite facies. Contacts are transposed and compositional layering is pervasive, but discontinuous in exposure; sedimentary structures are not preserved. Bryant interpreted the protoliths of the Farmington complex rocks as part of an Archean passive-margin sequence based largely on the lithologies present, the results of elemental analyses he reported, and a range of Archean $^{207}Pb/^{206}Pb$ ages from detrital zircons and Sm-Nd depleted mantle model ages >2.5 Ga presented in Hedge et al. (1983). Proposed protoliths include arkose; sandstone, including greywacke; shale; and metavolcanic rocks. In contrast, Shervais (2006) highlighted the range of mafic (and ultramafic) rock compositions and reinterpreted these rocks as part of an Archean accretionary mélange; however, Mueller et al. (2004) and Nelson et al. (2011) suggested that the Farmington sequence was Paleoproterozoic (ca. 1.7 Ga). Nelson et al. (2009) summarized the thermal history of these rocks and concluded that peak metamorphic conditions were reached sometime before 1.7 Ga (e.g., Barnett et al., 1993). Samples reported here were collected from the quartzite-gneiss-schist and migmatite map–units of Bryant (1988).

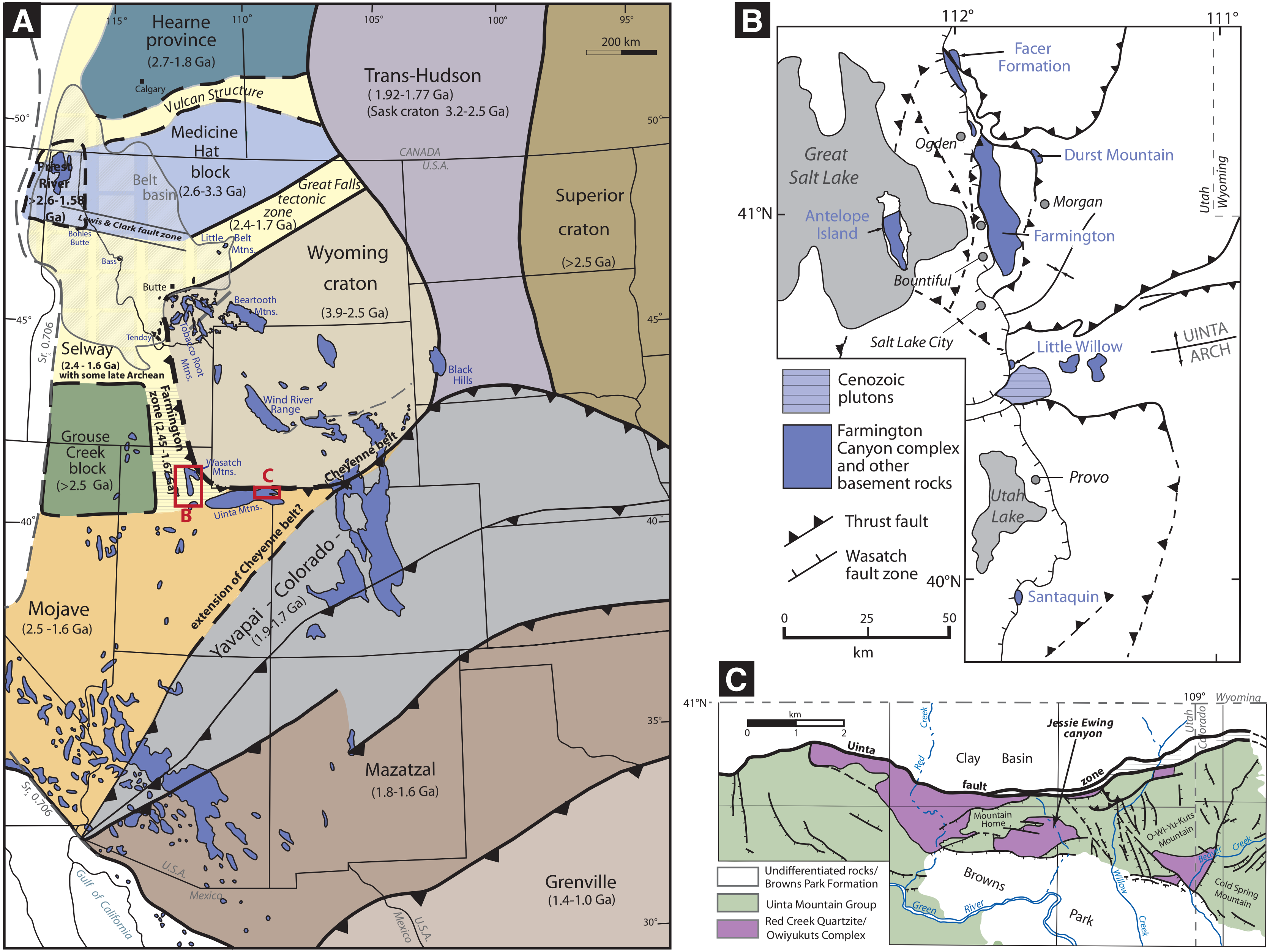

Figure 1. A. Generalized map of major basement provinces of southwestern Laurentia modified from Foster et al. (2006) and references therein. The approximate limit of thick Precambrian basement is shown by the dashed 0.706 $^{87}Sr/^{86}Sr$ initial ratio line. The two boxes show the locations of more detailed maps of the Farmington Canyon complex and other basement inliers along the Wasatch Mountain front (B, after Hedge et al., 1983), and the eastern Uinta Mountains (C, after Hansen, 1965). Exposures of the Red Creek quartzite were sampled in Jesse Ewing canyon and of the Owiyukuts complex on Owiyukuts Mountain. The Cheyenne belt is labeled in southeastern Wyoming where it is exposed and as a dashed line along the proposed extension along the Yavapai-Mojavia boundary. Exposures with ca. 2.4 Ga ages (U-Pb zircon) in southwestern Montana include the Tendoy, Tobacco Root, Ruby, and Gallatin Ranges (PP; Mueller et al. 2011). Latitude and longitude of individual samples in this study are in Table S1 (see footnote 1).

Little Willow Complex

A sample of quartzite was collected from an assemblage of meta-psammitic gneisses, schists, quartzites, and mafic amphibolites metamorphosed in the amphibolite facies. The rocks are exposed over a small area along the Wasatch front south of the Farmington Canyon complex and are informally referred to as the Little Willow complex (Fig. 1; Bryant, 1988; Nelson, 2002; Spencer et al., 2009).

Red Creek Quartzite and Owiyukuts Complex

Precambrian crystalline rocks exposed in the eastern Uinta uplift (e.g., Condie et al., 2001; Mueller et al., 2007; Dehler et al., 2010) were separated into two distinct lithologic associations by Sears et al. (1982): (1) Red Creek quartzite and (2) Owiyukuts complex. The Red Creek quartzite is a complex of primarily quartzite intercalated with lesser amounts of amphibolite and schist; metamorphism is in the amphibolite facies. The Red Creek rocks are in thrust contact with the underlying Owiyukuts complex and are unconformably overlain by the Neoproterozoic Uinta Mountain Group. The Owiyukuts complex consists of quartzofeldspathic gneisses and migmatites with locally developed leucosomes that were tentatively assigned an Archean age (Sears et al., 1982). The Red Creek complex was considered Proterozoic. Samples were collected from quartzofeldspathic gneisses and leucosomes (Owiyukuts complex) and meta-psammitic rocks of the Red Creek complex.

METHODS AND RESULTS

U-Pb analyses of all zircons were done by ion microprobe and guided by cathodoluminescense (CL) images (Fig. S1); details are available in the GSA Data Repository along with Sm-Nd data (ID-TIMS) and major element abundances (XRF) in Table S2[1]. All U-Pb ages discussed in the text are derived from $^{207}Pb/^{206}Pb$ ratios and reported at the 95% confidence level and all Th/U ratios are weight ratios from Table S1 (see footnote 1). Irrespective of location, most of the 197 analyses (Table S1 [see footnote 1]) can be readily assigned to one of two groups: (1) The majority of analyses (135) have Th/U >0.1, and have the highest probability of being magmatic and yielding primary age information regarding emplacement or provenance and, (2) Sixty-two zircons have Th/U <0.1, which typically reflects formation in oxidizing, hydrothermal conditions under which U is preferentially mobilized compared to Th, and such grains are typically interpreted as metamorphic (Rubatto, 2002). Despite the fact that many of these rocks have reached transitional amphibolite-granulite conditions, a majority of analyses (130, 66%) are 10% or less discordant. Of these 130 analyses, 38 have Th/U <0.1 and occur in both the Uinta (Owiyukuts) and Wasatch (Farmington) locations. Collectively, these data allow us to address two separate aspects of the evolution of these Precambrian rocks: (1) Primary ages (Th/U >0.1) help constrain the ages of crystallization of meta-igneous rocks, the provenance of the sedimentary protoliths, and to a lesser extent constrain the time of deposition of the sedimentary protoliths, and (2) Secondary or metamorphic ages (Th/U <0.1) record the time at which new zircon grew and likely mark the time of a thermal maximum, particularly in the migmatites. It is clear, however, that many samples with Th/U >0.1 have systematically degraded ages proportional to their Th/U ratio (Fig. 2A). Cathodoluminescence images (Fig. S1 [see footnote 1]) clearly show a range of textures and intergrowths of high-U (dark) and lower-U (light) zircon. The invasive nature of the high-U material seen in the CL images appears to have occurred at a range of scales, not all of which appear visible in these images or were separable with the ~35-μm beam of the ion probe. The effects of this invasive growth of hydrothermal zircon are evident in the declines in age with decreasing Th/U ratio in many data sets (Table S1 [see footnote 1]; Fig. 2A). For this reason, commonly utilized concordia (e.g., Figs. S2, S3 [see footnote 1]) and probability density diagrams (Fig. 3) do not provide the most useful insights into the U-Pb systematics of these zircons and any regression age is likely to be negatively affected by this phenomenon. Consequently, age-Th/U plots provide a better opportunity to assess these data (e.g., Fig. 2).

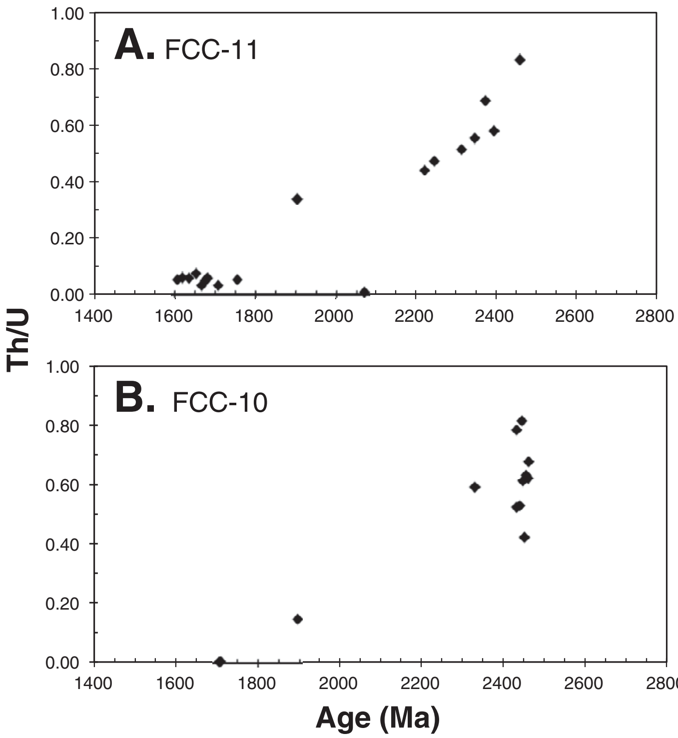

Figure 2. Plot of Th/U versus $^{207}Pb/^{206}Pb$ age for migmatite sample FCC-11 (A) showing correlation between Th/U and age and for quartzofeldspathic gneiss sample FCC-10 (B) showing no correlation between Th/U and age. Although the oldest ages are essentially identical in the two samples, data from FCC-10 provide the best estimate of the crystallization age of the protolith (Fig. S2 [see footnote 1]).

DISCUSSION

Depositional and Emplacement Ages

A Paleoproterozoic depositional age for the Farmington sequence is suggested by the 2.446 ± 0.011 Ga age calculated for all high-Th/U grains that are less than 10% discordant from sample FCC-10 (Table S1; Figs. S2, S4 [see footnote 1]; Fig. 2B). This sample is from a layer of quartzofeldspathic gneiss in the quartzite-schist-gneiss map-unit of Bryant (1988). This sample is mineralogically (quartz-biotite-feldspar-garnet) and compositionally (SiO_2 of ~74%; Table S2 [see footnote 1]) similar to many examples reported by Bryant (1988) for the gneisses in this map unit. Layering is transposed in this unit and no sedimentary structures are preserved. An igneous protolith, as opposed to a sedimentary protolith, is

[1]GSA Data Repository Item 2011350, chemical and isotopic data (and plots), images of selected zircons analyzed, and an expanded methods section, is available at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

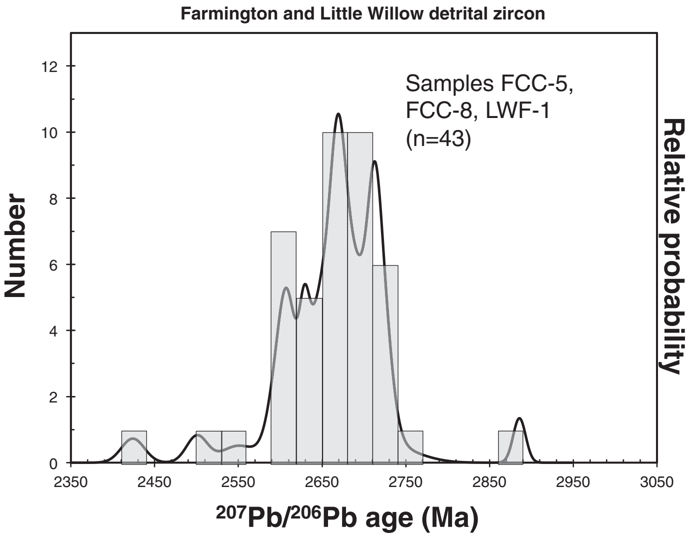

Figure 3. Probability density function and histograms (Isoplot; Ludwig, 2003) for U-Pb ages of 46 detrital zircons from metasedimentary rocks from the Farmington and Little Willow complexes with Th/U >0.1 (samples FCC-5, FCC-8, LWF-1).

suggested because: (1) The ten oldest zircons give a precise age; (2) There is no correlation of Th/U and age to suggest that the ages of the oldest grains have been degraded by metamorphism; (3) Zircon morphologies and zoning in analyzed grains appear igneous; (4) Lack of evidence of sedimentary input, e.g., no Archean zircons and low TiO_2 content (0.4%); and (5) Little indication of weathering in its major element composition (e.g., relatively low Al_2O_3 content, ~12%). If this is not the case and the rock does have a sedimentary protolith (even an arkosic one), then the depositional age of the Farmington sequence must be <2.46 Ga. If the rock is metaplutonic, then the ca. 2.46 Ga age would indicate the sedimentary sequence was older than the crystallization age of FCC-10. "Older" in this case could refer to a penecontemporaneous, hypabyssal intrusion, or emplacement at ca. 2.46 Ga into a substantially older sequence that can only be constrained as younger than the youngest detrital zircon. In this data set, the youngest detrital zircon with Th/U >0.1 is 2.42 ± 0.03 Ga (5% discordant) from sample FCC-8 (Table S1 [see footnote 1]), which is within error of the 2.46 ± 0.01 Ga age of sample FCC-10. For high-grade, quartzofeldspathic rocks in transposed sequences, however, it is rarely possible to unequivocally certify a compositional layer to have a specific protolith. The similarity in age of the youngest detrital zircon and the age of igneous zircons in FCC-10, however, suggests a penecontemporaneous, igneous protolith is probable.

The lack of correlation between age and Th/U ratio in FCC-10 contrasts with results from FCC-11, which clearly shows a significant age-variation proportional to Th/U. As shown in Figure 2A, however, the upper limit of age and Th/U in sample FCC-11 (migmatitic gneiss) is 2.458 ± 0.012 Ga (Table S1 [see footnote 1]). A similar observation can be made for FCC-12, also a migmatitic gneiss, which has a maximum age of 2.455 ± 0.022 Ga and no Archean grains. Considering the impact that metamorphism has had on these rocks and their zircons, these ages must be taken as minima. Collectively, however, these data suggest an emplacement/depositional/eruption age of ca. 2.45 Ga for the protoliths of these gneisses in the Farmington complex.

Data from these three meta-igneous–metamorphic rocks contrast with samples from layers that appear to have sedimentary protoliths. Sample FCC-5, for example, is from a quartzite that is part of the quartzite-schist-gneiss unit (afs) of Bryant (1988). The oldest grains in this sample show no or very limited correlation between Th/U and age, and all are Archean (2.62–2.74 Ga; Table S1 [see footnote 1]; Fig. 3). Sample FCC-8 has a similar distribution, but also contains 2.42 and 2.50 Ga detrital grains (Fig. 3). Ages of detrital zircons from a quartzite from the Little Willow complex are all Archean and the range of ages is similar to the range of Archean ages in samples from the Farmington complex, i.e., from 2.6 to 2.7 Ga for grains that are <10% discordant (Table S1 [see footnote 1]). Older ages from more discordant grains, however, extend the minimum age for the detrital component to ca. 2.9 Ga (Fig. 3) in the Little Willow complex and, along with Archean Sm-Nd model ages, strongly suggest a significant contribution from Archean crust in both the Farmington and Little Willow complexes (e.g., Hedge et al., 1983; Nelson et al., 2011; Table S2 [see footnote 1]). This crust was likely the southern Wyoming Province (Frost et al., 1998; southern accreted terranes of Chamberlain et al., 2003), which also shed detritus, including zircons with a similar, limited range of Archean ages, into the Uinta Mountain Group in the Neoproterozoic (e.g., Mueller et al., 2007; Dehler et al., 2010).

In the Uinta Mountains, samples from neither the Owiyukuts nor Red Creek complexes provided evidence of magmatic emplacement. In the Owiyukuts complex, zircons from a quartz-rich metasedimentary rock (OWK-2) showed a pattern of decreasing age with decreasing Th/U similar to that seen in the Farmington rocks (Fig. 4A). This suggests ages from all of these zircons should be viewed as minima, but does not change the interpretation of an Archean provenance similar to that of the Farmington and Little Willow complexes. The youngest detrital grain (<10% discordant) gave a minimum age of 2.42 ± 0.02 Ga, again similar to Farmington. The single analysis with Th/U <0.1 and <10%

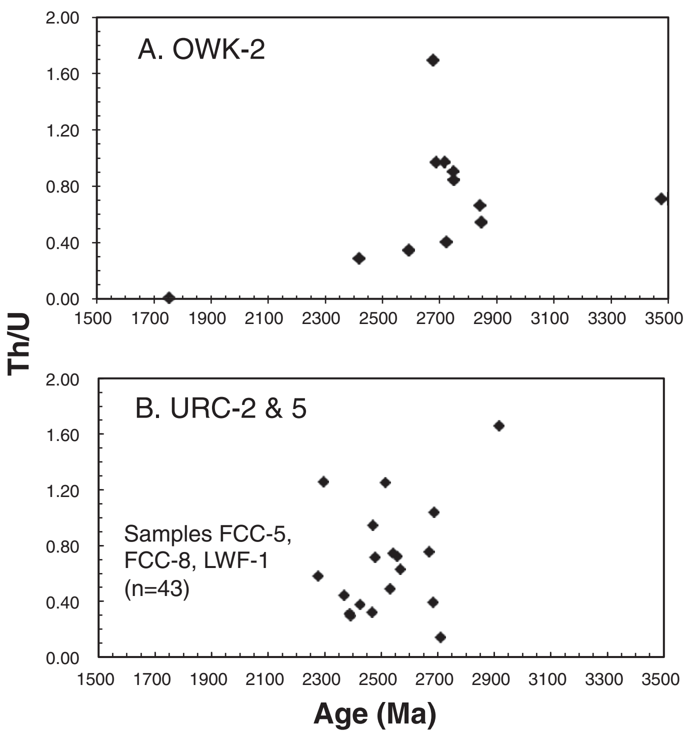

Figure 4. Plot of age versus Th/U for zircons from: (A) a quartz-rich metasedimentary rock from the Owiyukuts complex (OWK-2) and, (B) an aggregate of measurements for two quartz-rich metasedimentary rocks from the Red Creek complex (URC-2 and 5).

discordant gave an age of 1.75 Ga. This measurement was made on an overgrowth and is –4% discordant, which suggests it was in place prior to 1.75 Ga. Nelson et al. (2011) also reported an U-Pb age of 1.74 Ga for a zircon from an Owiyukuts paragneiss, but considered the grain detrital and suggested it provided an upper limit for deposition of the protolith. Unfortunately, a Th/U ratio was not reported for this analysis, so it is unclear if grains in this sample conform to the pattern of decreasing age with decreasing Th/U reported here and/or may be metamorphic (Th/U <0.1). Ages of detrital zircons from two quartz-rich metasedimentary rocks from the Red Creek complex that are <10% discordant are very similar in their age distributions with only a limited co-variance between Th/U and age (Fig. 4B). This covariation suggests that these ages are also best viewed as minima; however, the limited nature of the covariation suggests that the youngest grains may at least loosely constrain the time of deposition. If so, the youngest of these ages (ca. 2.3 Ga) suggests an upper limit for the depositional age of these rocks that is only slightly younger than the limit for Owiyukuts deposition (ca. 2.4 Ga). It is also important to note the presence of additional 2.4–2.5 Ga grains in both Red Creek samples (URC-2, 5; Table S1 [see footnote 1]), comparable to the youngest detrital grains in the Farmington complex. Most grains in the metasedimentary lithologies from both the Red Creek and Owiyukuts sequences, however, are Archean with an upper limit of ca. 2.9 Ga for grains that are <10% discordant; the inclusion of more discordant grains increases the upper limit to a minimum of ca. 3.4 Ga. A dominant Archean provenance is supported by Sm-Nd depleted mantle model ages for the Red Creek rocks (2.6–3.5 Ga), which are also comparable to those from the Farmington complex (Table S2 [see footnote 1]).

Metamorphism

In terms of U-Pb systematics, the positive correlation between Th/U and age in many samples makes it clear that metamorphism has altered primary age information in many zircons. Because this relationship is gradational, it is not possible to derive realistic estimates of metamorphic episodes from such grains. Instead, a focus on grains with the lowest Th/U ratios that do not show a relationship between Th/U and age provides the best opportunity to estimate the time of growth of new zircon. New zircon occurs as individual grains and as new growth on older cores (data for overgrowths recognizable in CL images labeled as T or R in Table S1; Fig. S1 [see footnote 1]) in both migmatitic leucosomes and in the metamorphic rocks that did not undergo anatexis. In the Farmington migmatites (FCC-11, 12), zircons with Th/U ratios between 0.02 and 0.11 and discordance from 0%–3% define a distinct age-range compared to the grains with higher Th/U (Table S1 [see footnote 1]). Data from 16 of 17 analyses yield an age of 1.665 ± 0.018 Ga. Similarly, in the Owiyukuts complex, low Th/U zircons are the dominant type in the two leucosomes sampled. The mean age for the 12 grains that are 10% or less discordant from both samples is 1.677 ± 0.010 Ga (Fig. S3 [see footnote 1]).

The similarity of these ages suggests a common age of metamorphism. An aggregation of data for all zircons that are 10% or less discordant and have Th/U <0.1 from all samples (migmatitic and non-migmatitic) from all locations is shown in Figure 5. These ages range from ca. 1.6–2.1 Ga, but show a significant concentration in a narrow range between 1.65 and 1.75 Ga as indicated by the zircons from both the Farmington and Owiyukuts migmatites. Excluding the three oldest ages as analytically mixed ages (e.g., Fig. S1 [see footnote 1]; Strickland et al., 2011), yields a mean age of 1.674 ± 0.012 Ga. This date is within error of the age calculated for zircons solely from low Th/U grains from the migmatites and likely provides the best estimate for the time of migmatization and metamorphism.

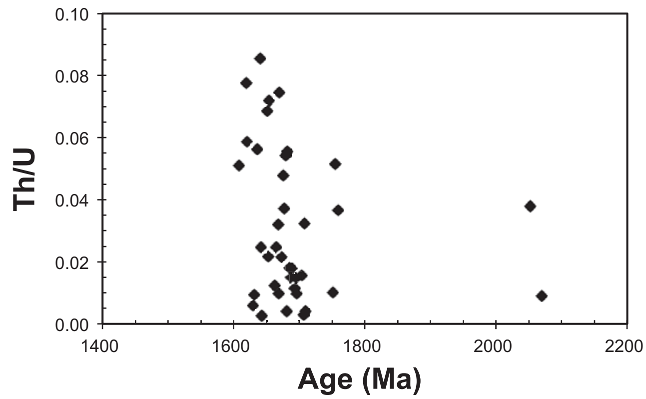

Figure 5. A plot of Th/U versus age for all zircons from all localities with Th/U <0.1 and discordance <10% (38 grains) showing the strong concentration of ages at ca. 1.67 Ga and lack of correlation between age and Th/U.

Consequently, it appears most probable that all locales from the eastern Uinta Mountains (Owiyukuts, Red Creek) to the central Wasatch Range (Farmington Canyon, Little Willow) experienced intense metamorphism at ca. 1.67 Ga. This estimate for the time of metamorphism is similar to the U-Pb zircon age of ca. 1.69 Ga reported for the protolith of a biotite gneiss from the Farmington complex on Antelope Island in the Great Salt Lake (Nelson et al., 2011). All 20 of those grains, however, had Th/U <0.1 and may have formed in a leucosome with an origin similar to the migmatitic leucosomes represented by FCC-11 and 12. There is no evidence in these data to suggest any significant, high-T metamorphic event subsequent to ca. 1.67 Ga, in agreement with Nelson et al. (2009).

IMPLICATIONS

These new constraints on the origin and evolution of the Precambrian rocks of northeastern Utah have several important implications, including:

(1) Evidence of active tectonism and magmatism at ca. 2.45 Ga is an unusual aspect of the global geologic record (e.g., Voice et al., 2011). Although ca. 2.45 Ga crust in Laurentia is largely limited to the Taltson province of northwestern Canada (e.g., McNicoll et al., 2000; Schultz et al., 2007), Kellogg et al. (2003) report ca. 2.45 Ga orthogneiss from a basement culmination in the Cordilleran thrust belt in the Tendoy Mountains of southwestern Montana (Fig. 1), Mueller et al. (1996) report xenocrystic zircon in the Tobacco Root batholith of southwestern Montana of this age, Mueller et al. (2011) report evidence for migmatization at this time in southwestern Montana, and Foster et al. (2011) report xenocrystic zircon and Hf-isotopic data that indicate components of the Pioneer batholith were derived from crust of this age. These occurrences along with the presence of ca. 2.45 Ga magmatism in the Farmington Canyon complex, and probably in the eastern Uinta region as well based on ages of detrital zircons, suggest crust of similar age may extend along the entire western margin of the Wyoming craton (Farmington zone, Fig. 1); similar ages have also been reported from eastern Wyoming (e.g., Baggot Rocks batholith: Premo and Van Schmus, 1989). The lack of corresponding magmatism along the western interior of the Wyoming craton and the dominance of metasedimentary rocks with Wyoming-age detrital zircons in rocks deposited ca. 2.45 Ga ago in the Farmington zone suggest that these early Paleoproterozoic crustal additions were not formed as a consequence of east-directed subduction. More likely, these additions may have formed in a rift or trans-tensional environment correlative to the ca. 2.48 Ga rifting proposed for the eastern margin of the Wyoming craton north of the

Cheyenne belt (e.g., Dahl et al., 2006) and/or related to the global episode of rifting at ca. 2.45 Ga that led to the break-up of the supercontinent Kenorland (e.g., Heaman, 1997).

(2) Constraining the relationship between Mojavia and (A) crust of roughly comparable age to the east (Yavapai-Colorado), (B) older crust to the northeast (Wyoming), and (C) the mixture of Paleoproterozoic and Archean crust north of (or in northern) Mojavia (central and northern Great Basin) is critical to understanding the evolution of southwestern Laurentia and its metallogeny and, by extension, Paleoproterozoic global geodynamics and crustal growth (e.g., Rodriguez and Williams, 2008; Premo et al., 2008). Numerous studies of the Sm-Nd and U-Pb systematics of Proterozoic and younger igneous rocks of the Great Basin (e.g., Zartman, 1974; Bennett and DePaolo, 1987; Ramo and Calzia, 1998; Wooden and Miller, 1990; Hill and Bickford, 2001; Eisele and Isachsen, 2001; Duebendorfer et al., 2006; Nelson et al., 2011) have been interpreted to indicate that the crust of Mojavia is characterized by more extensive recycling of older crust (>2.0 Ga Sm-Nd model ages) than crust in the other Proterozoic accreted terranes of southwestern Laurentia (<2.0 Ga Sm-Nd model ages). The older model ages attributed to Mojave crust (e.g., 2.6 Ga; Ramo and Calzia, 1998) have typically been interpreted to provide a minimum estimate of the age of the lithosphere because of the likely involvement of mantle-derived melts in the formation of post-Archean magmas. Nelson et al. (2011), however, proposed that the evolved isotopic signature of Mojave crust results from a layer of Archean (Wyoming) detritus overlaying more juvenile Yavapai crust that was intimately reworked during Proterozoic and Phanerozoic orogenesis as suggested by Premo et al. (2008) for the Angel Lake gneiss of Nevada. Although the dilution of the more ancient isotopic signals in younger magmas makes it difficult to use them to accurately define province boundaries, the Proterozoic remobilization of Archean crust via its detritus in the Farmington zone at ca. 2.45 and ca. 1.67 Ga may provide insight into the initial incorporation of Archean crust (as detritus) in the formation of Proterozoic Mojave crust. This is compatible with previous proposals of a genetic relationship between Wyoming and Mojavia based on unique U-Th-Pb systematics and Nd model ages (e.g., Bennett and DePaolo, 1987; Wooden and Dewitt, 1991; Nelson et al., 2011). The general paucity of Archean detrital zircons in Proterozoic metasedimentary rocks that match with age spectra from the Wyoming craton (Barth et al., 2009; Shufeldt et al., 2010), however remains a substantial problem for this hypothesis. The presence of age peaks at ca. 2.48 Ga in the age spectra of the Vishnu schist, however, suggests a potential tie with the ca. 2.45 Ga magmatism recognized in the Farmington zone. Alternatively, the lack of >2.5 Ga detrital zircon ages may simply indicate that Mojave crust originally formed independently at ca. 2.5 Ga. If so, its characteristic low Sm/Nd and high U/Pb history may derive from a plume-related origin (e.g., Condie, 1999; Mueller et al., 2010; Mueller and Wooden, in press).

Regardless of its derivation, the more evolved nature of Mojave crust relative to Yavapai-Colorado and Mazatzal crust, and its less evolved nature relative to Wyoming crust, suggests that the Cheyenne belt may not extend along strike into the Great Basin as the northern boundary of Mojavia (e.g., Premo et al., 2008) as suggested by numerous workers (e.g., Sears et al., 1982; Lush et al., 1988; Bryant, 1988; Rodriguez and Williams, 2008). An alternative to this model is that the Cheyenne belt, as a structural feature that might have originated as a rifted margin (e.g., Jones, 2011), may bend southward and merge into the Mojave-Yavapai boundary zone, thereby retaining its character as a fundamental Paleoproterozoic boundary between more- and less-evolved lithosphere (e.g., Bennett and DePaolo, 1987; Karlstrom et al., 2002). The suggestion by Nelson et al. (2011) that the Cheyenne belt should be viewed strictly as an Archean–Proterozoic collisional feature and, therefore, lie east of the Farmington zone is a more difficult geometry to reconcile with metamorphism in the Farmington zone at ca. 1.67 Ga and the Great Falls tectonic zone at 1.75–1.86 Ga in light of: (1) The projected northeast-directed collisional vectors required to accommodate the formation of the Great Falls tectonic zone at 1.75–1.86 Ga with north-directed subduction (i.e., away from the Wyoming craton; Mueller et al., 2002; 2005); (2) The high angle of intersection between the Great Falls tectonic zone and the proposed extension of the Cheyenne belt; and (3) The lack of evidence for a Paleoproterozoic magmatic arc along the proposed westward and northern extension of the Cheyenne belt in and along the western Wyoming Province. It remains unclear whether Archean rocks and detritus west of the Farmington zone (e.g., Leeman et al., 1985; Lush et al., 1988; Premo et al., 2008; Strickland et al., 2011) are derived from the Wyoming Province, or represent crustal components of later accreted terranes (e.g., Foster et al., 2006).

(3) The aggregate 1.674 ± 0.012 Ga age for metamorphism recorded in the Farmington Canyon and Owiyukuts complexes suggests that these ages were produced during a substantial tectonic event that appears to have buried the southwestern corner of the Wyoming craton, including the Farmington complex and the early Paleoproterozoic basement of the Uinta uplift. The lack of evidence for coeval arc magmatism in the western or southwestern parts of the Wyoming Province and the presence of calc-alkaline batholiths in Mojavia at this time suggest aggregated Mojave (± Yavapai-Colorado) crust was likely thrust over the southwestern corner of the Wyoming craton at ca. 1.67 Ga along an east- or northeast-directed vector (subduction to the south-southwest). If so, the geodynamics of this collision would be compatible with development of the Great Falls tectonic zone along the Wyoming craton's northern boundary beginning at ca. 1.86 Ga with north-directed subduction beneath the Medicine Hat block (e.g., Mueller et al., 2005). The thrusting in southwestern Laurentia may represent a component of obduction following collapse of an ocean of unknown size that also closed due to subduction directed away from the Wyoming craton. This would be true regardless of whether Mojavia had ancient ties to Wyoming and would be consistent with the intercalation of mafic and ultramafic rocks with possible oceanic affinities within the Farmington complex (e.g., Bryant, 1988; Shervais, 2006). Most importantly, the consistent age of metamorphism recorded in zircons from the Farmington and Owiyukuts complexes and the widespread record of ca. 1.67 Ga tectonism and magmatism throughout the accreted Paleoproterozoic terranes of southwestern Laurentia, but especially in the Mojave-Yavapai boundary zone (e.g., Wooden and Miller, 1990; Whitmeyer and Karlstrom, 2007; Amato et al., 2008), suggests this episode of tectonism may reflect the (near) final movements associated with the incorporation of these terranes into Laurentia.

In detail, tectonism at ca. 1.67 Ga is significantly younger than the age of ca. 1.75 Ga proposed for Colorado-Wyoming convergence along the Cheyenne belt (e.g., Chamberlain, 1998; Duebendorfer et al., 2006; Jones et al., 2010) and the 1.78 Ga metamorphism of 2.45 Ga and older gneisses from the Great Falls tectonic zone in southwestern Montana (Fig. 1; Mueller et al., 2005; Foster et al., 2006). The ~100 m.y. differential and the lack of geophysical evidence for subduction beneath the Wyoming craton along strike of the Cheyenne belt (Deep Probe data; Karlstrom et al., 2005) support a diachronous, oblique convergence between the Wyoming and combined Mojave-Colorado-Yavapai–crustal blocks similar to that proposed for the Wyoming–Medicine Hat collision along the Great Falls tectonic zone (Mueller et al., 2005) and are not compatible with models calling for ca. 1.7 Ga collision and subduction beneath the western margin of the Wyoming craton (e.g., Nelson et al., 2011).

CONCLUSIONS

U-Pb ages of magmatic zircons from meta-igneous and metasedimentary rocks of the Farmington Canyon complex, ubiquitous Neoarchean detrital zircons from throughout the study area, and Archean Sm-Nd depleted mantle model ages of metasedimetary and meta-igneous rocks suggest rift-related magmatic and depositional systems were likely present along the southwestern margin of the Wyoming craton in the early Paleoproterozoic (ca. 2.45 Ga). The provenance of the sedimentary component appears to be largely from the southern Wyoming Province. The common age of metamorphism experienced by these rocks (1.674 ± 0.012 Ga) and similar ages recorded by magmatic rocks in the Mojave-Yavapai boundary zone may reflect the time of final juxtaposition of Mojavia and perhaps other accreted terranes of southwestern Laurentia along a common boundary initiated by ca. 2.45 Ga rifting of the Wyoming craton and subsequent oblique collision(s) (Mueller et al., 2005). In addition, the unique Paleoproterozoic age and composition of rocks in the Farmington zone places a new constraint on any crust proposed as a conjugate to southwestern Laurentia prior to Neoproterozoic rifting, e.g., AUSWUS (Australia southwestern U.S.), SWEAT (southwestern U.S. East Antarctica), Siberia, etc. (e.g., Moores, 1991; Burrett and Berry, 2000; Karlstrom et al., 2001; Sears and Price, 2003).

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REFERENCES CITED

Amato, J., Boullion, A., Serna, A., Sanders, A., Farmer, G., Gehrels, G., and Wooden, J., 2008, Evolution of the Mazatzal province and the timing of the Mazatzal orogeny: Insights from U-Pb geochronology and geochemistry of igneous and metasedimentary rocks in southern New Mexico: Geological Society of America Bulletin, v. 120, p. 328–346, doi:10.1130/B26200.1.

Barnett, D., Bowman, J., and Smith, H., 1993, Petrologic and geochronologic studies in the Farmington Canyon complex, Wasatch Mountains, Utah: Utah Geological Survey Contract Report 93-5, p. 34.

Barth, A., Wooden, J., Coleman, D., and Vogel, M., 2009, Assembling and disassembling California: A zircon and monazite geochronologic framework for Proterozoic crustal evolution in southern California: Journal of Geology, v. 117, p. 221–239.

Bennett, V., and DePaolo, D., 1987, Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping: Geological Society of America Bulletin, v. 99, p. 674–685, doi:10.1130/0016-7606(1987)99<674:PCHOTW>2.0.CO;2.

Bryant, B., 1988, Geology of the Farmington Canyon complex, Wasatch Mountains, Utah: U.S. Geological Survey Professional Paper 1476, 54 p.

Burrett, C., and Berry, R., 2000, Proterozoic Australia-western United States (AUSWUS) fit between Laurentia and Australia: Geology, v. 28, p. 103–106, doi:10.1130/0091-7613(2000)28<103:PAUSAF>2.0.CO;2.

Chamberlain, K., 1998, Medicine Bow orogeny: Timing of deformation and model of crustal structure produced during continent-arc collision, ca. 1.78 Ga, southeastern Wyoming: Rocky Mountain Geologist, v. 33, p. 259–277.

Chamberlain, K., Frost, C., and Frost, R., 2003, Early Archean to Mesoproterozoic evolution of the Wyoming Province: Archean origins to modern lithospheric architecture: Canadian Journal of Earth Sciences, v. 40, p. 1357–1374, doi:10.1139/e03-054.

Condie, K. 1999, Mafic crustal xenoliths and the origin of the lower continental crust: Lithos, v. 46, p. 95–101.

Condie, K., Lee, D., and Farmer, G., 2001, Tectonic setting and provenance of the Neoproterozoic Uinta Mountain and Big Cottonwood groups, northern Utah: Constraints from geochemistry, Nd isotopes, and detrital modes: Sedimentary Geology, v. 141, p. 443–464, doi:10.1016/S0037-0738(01)00086-0.

Dahl, P., Hamilton, M., Wooden, J., Foland, K., Frei, R., MacCombs, J., and Holm, D., 2006, 2480 Ma mafic magmatism in the northern Black Hills, South Dakota: A new link connecting the Wyoming and Superior cratons: Canadian Journal of Earth Sciences, v. 43, p. 1579–1600, doi:10.1139/e06-066.

Dehler, C., Fanning, M., Link, P., Kingsbury, E., and Rybczynski, D., 2010, Maximum depositional age and provenance of the Uinta Mountain Group and Big Cottonwood Formation, northern Utah: Paleogeography of rifting western Laurentia: Geological Society of America Bulletin, v. 122, p. 1686–1699, doi:10.1130/B30094.1.

Duebendorfer, E.M., and Houston, R.S., 1987, Proterozoic accretionary tectonics at the southern margin of the Archean Wyoming craton: Geological Society of America Bulletin, v. 98, p. 554–568, doi:10.1130/0016-7606(1987)98<554:PATATS>2.0.CO;2.

Duebendorfer, E., Chamberlain, K., and Fry, B., 2006, Mojave-Yavapai boundary zone, SW United States: A rifting model for the formation of an isotopically mixed crustal boundary zone: Geology, v. 34, p. 681–684, doi:10.1130/G22581.1.

Eisele, J. and Isachsen, C., 2001, Crustal growth in southern Arizona: U-Pb geochronologic and Sm-Nd isotopic evidence for addition of the Paleoproterozoic Cochise block to the Mazatzal Province: American Journal of Science, v. 301, p. 773–797.

Foster, D., Mueller, P., Vogl, J., Mogk, D., Wooden, J., and Heatherington, A., 2006, Proterozoic evolution of the western margin of the Wyoming Craton: Implications for the tectonic and magmatic evolution of the northern Rocky Mountains: Canadian Journal Earth Science, v. 43, p. 1601–1619.

Foster, D.A., Mueller, P.A., Heatherington, A., and Gifford, J.N., 2011, Hf-isotopes of igneous zircon from Cretaceous batholiths reveal ca. 1.9 and 1.5 Ga mafic lower crust in the northern Rocky Mountains: Geological Society of America Abstracts with Programs, v. 43, no. 4, p. 72.

Frost, B.R., Chamberlain, K.R., Swapp, S., Frost, C.D., and Hulesbosch, T.P., 2000, Late Archean structural and metamorphic history of the Wind River Range: Evidence for a long-lived active margin on the Wyoming craton: Geological Society of America Bulletin, v. 112, p. 564–578, doi:10.1130/0016-7606(2000)112<564:LASAMH>2.0.CO;2.

Frost, C., Frost, B., Chamberlain, K., and Hulsebosch, T., 1998, The late Archean history of the Wyoming Province as recorded by granitic magmatism in the Wind River Range, Wyoming: Precambrian Research, v. 89, p. 145–173.

Hansen, W., 1965, Geology of the Flaming Gorge area, Utah-Colorado-Wyoming: U.S. Geological Survey Professional Paper 490, 196 p.

Heaman, L., 1997, Global mafic magmatism at 2.45 Ga: Remnants of an ancient large igneous province: Geology, v. 25, p. 299–302, doi:10.1130/0091-7613(1997)025<0299:GMMAGR>2.3.CO;2.

Hedge, C., Stacey, J., and Bryant, B., 1983, Geochronology of the Farmington Canyon Complex, Wasatch Mountains, Utah: Geological Society of America, v. 157, p. 37–44.

Hill, B., and Bickford, M., 2001, Paleoproterozoic rocks of central Colorado: Accreted arcs or extended older crust: Geology, v. 29, p. 1015–1018, doi:10.1130/0091-7613(2001)029<1015:PROCCA>2.0.CO;2.

Hills, F., and Houston, R. 1979, Proterozoic tectonics of the central Rocky Mountains, North America: University of Wyoming, Contributions to Geology, v. 17, p. 89–109.

Jones, D., 2011, Was the Cheyenne belt once a transform margin?: Implications of detrital zircon ages from the Green Mountain arc and Barber Lake block, southern Wyoming: Geological Society of America Abstracts with Programs, v. 43, p. 71.

Jones, J., Snoke, A., Premo, W., and Chamberlain, K., 2010, New model for Paleoproterozoic orogenesis in the Cheyenne belt region: Evidence from the geology and U-Pb geochronology of the Big Creek Gneiss, southeastern Wyoming: Geological Society of America Bulletin, v. 122, p. 1877–1898, doi:10.1130/B30164.1.

Karlstrom, K.E., and Houston, R.S., 1984, The Cheyenne Belt: Analysis of a Proterozoic suture in southern Wyoming: Precambrian Research, v. 25, p. 415–446, doi:10.1016/0301-9268(84)90012-3.

Karlstrom, K., Ahall, K.-I., Harlan, S., Williams, M., McLelland, J., and Geissman, J., 2001, Long-lived (1.8–1.0) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia: Precambrian Research, v. 111, p. 5–30, doi:10.1016/S0301-9268(01)00154-1.

Karlstrom, K., and CD-ROM Working Group, 2002, Structure and evolution of the lithosphere beneath the Rocky Mountains: Initial results from the CD-ROM experiment: Geology Today, v. 12, p. 4–10.

Karlstrom, K., and the CD-ROM Working Group, and 53 others, 2005, Synthesis of results from the CD-ROM experiment: 4D image of the lithosphere beneath the Rocky Mountains and implications for understanding the evolution of continental lithosphere, *in* Karlstrom, K., and Keller, R., eds., The Rocky Mountains Region: An Evolving Lithosphere: American Geophysical Union Monograph 154, p. 421–441.

Kellogg, K., Snee, L., and Unruh, D., 2003, The Mesoproterozoic Beaverhead impact structure and its tectonic setting, Montana and Idaho $^{40}Ar/^{39}Ar$ and U-Pb constraints: The Journal of Geology, v. 111, p. 639–652, doi:10.1086/378339.

Leeman, W., Menzies, M., Matty, D., and Embree, G., 1985, Strontium, neodymium, and lead isotopic compositions of deep crustal xenoliths from the Snake River Plain: Evidence for Archean basement: Earth and Planetary Science Letters, v. 75, p. 354–368, doi:10.1016/0012-821X(85)90179-7.

Ludwig, K. R., 2003, Isoplot 3.09, A Geochronological Toolkit for Microsoft Excel: Berkeley Geochronology Center, Special Publication no. 4, 70 p.

Lush, A.P., McGrew, A.J., Snoke, A.W., and Wright, J.E., 1988, Allochthonous Archean basement in the northern East Humblolt Range, Nevada: Geology, v. 16, p. 349–353, doi:10.1130/0091-7613(1988)016<0349:AABITN>2.3.CO;2.

McNicoll, V., Theriault, R., and McDonough, M., 2000, Taltson basement gneissic rocks: U-Pb and Nd isotopic constraints on the basement to the Paleoproterozoic Taltson magmatic zone, northeastern Alberta: Canadian Journal of Earth Sciences, v. 37, p. 1575–1596, doi:10.1139/e00-034.

Moores, E., 1991, The SWEAT connection: A hypothesis: Geology, v. 19, p. 425–428, doi:10.1130/0091-7613(1991)019<0425:SUSEAS>2.3.CO;2.

Mueller, P., and Wooden, J., in press, Trace element and Lu-Hf systematics in Hadean-Archean detrital zircons: Implications for crustal evolution: The Journal of Geology.

Mueller, P., Heatherington, A., D'Arcy, K., Wooden, J., and Nutman, A., 1996, Contrasts between Sm-Nd and U-Pb zircon systematics in the Tobacco Root batholith, Montana: Implications for the determination of crustal age provinces: Tectonophysics, v. 265, p. 169–179, doi:10.1016/S0040-1951(96)00151-5.

Mueller, P., Heatherington, A., Kelley, D., Wooden, J., and Mogk, D., 2002, Paleoproterozoic crust within the Great Falls Tectonic Zone: Implications for the assembly of southern Laurentia: Geology, v. 30, p. 127–130, doi:10.1130/0091-7613(2002)030<0127:PCWTGF >2.0.CO;2.

Mueller, P., Foster, D., Mogk, D., and Wooden, J., 2004, New insights into the Proterozoic evolution of the western margin of Laurentia and their tectonic implications: Geological Society of America Abstracts with Programs, v. 36, p. 404.

Mueller, P., Burger, H., Wooden, J., Brady, J., Cheney, J., Harms, T., Heatherington, A., and Mogk, D., 2005, Age and tectonic implications of Paleoproterozoic metamorphism in the northern Wyoming Province: The Journal of Geology, v. 113, p. 169–179, doi:10.1086/427667.

Mueller, P., Foster, D., Mogk, D., Wooden, J., and Vogl, J., 2007, Detrital mineral chronology of the Uinta Mountain Group: Implications of the Grenville flood in SW Laurentia: Geology, v. 35, p. 431–434, doi:10.1130/G23148A.1.

Mueller, P., Wooden, J., Mogk, D., Henry, D., and Bowes, D., 2010, Rapid growth of an Archean continent by arc magmatism: Precambrian Research, v. 183, p. 70–88, doi:10.1016/j.precamres.2010.07.013.

Mueller, P., Wooden, J., and Mogk, D., 2011, 2450 Ma metamorphism recorded in 3250 Ma gneisses, Gallatin Range, Montana: Northwest Geology, v. 40, p. 1–8.

Nelson, S., Harris, R., Dorais, M., Heizler, M., Constenius, K., and Barnett, D., 2002, Basement complexes in the Wasatch fault, Utah, provide new limits on crustal accretion: Geology, v. 30, p. 831–834, doi:10.1130/0091-7613(2002)030<0831:BCITWF>2.0.CO;2.

Nelson, S., Harris, R., Kowalis, B., Dorais, M., Constenius, K., Heizler, M., and Barnett, D., 2009, The long-term burial and exhumation history of basement blocks in the footwall of the Wasatch fault, Utah: Rocky Mountain Geology, v. 44, p. 103–119, doi:10.2113/gsrocky.44.2.103.

Nelson, S., Hart, G., and Frost, C., 2011, A reassessment of Mojavia and a new Cheyenne Belt alignment in the eastern Great Basin: Geosphere, v. 7, p. 513–527, doi:10.1130/GES00595.1.

Premo, W., and Van Schmus, W.R., 1989, Zircon geochronology of Precambrian rocks in southeastern Wyoming and northern Colorado, *in*, Grambling, J., and Tewksbury, B., eds., Proterozoic Geology of the Southern Rocky Mountains: Geological Society of America Special Paper 235, p. 13–32.

Premo, W., Castineiras, P., and Wooden, J., 2008, SHRIMP-RG U-Pb isotopic systematics of zircon from the Angel lake orthogneiss, East Humboldt Range, Nevada: Is this really Archean crust?: Geosphere, v. 4, p. 963–975, doi:10.1130/GES00164.1.

Ramo, T., and Calzia, J., 1998, Nd isotopic compositions of cratonic rocks in the southern Death Valley region: Evidence for a substantial Archean source component in Mojavia: Geology, v. 26, p. 891–894, doi:10.1130/0091-7613(1998)026<0891:NICOCR>2.3.CO;2.

Rodriguez, B., and Williams, J., 2008, Tracking the Archean-Proterozoic suture zone in the northeastern Great Basin, Nevada and Utah: Geosphere, v. 4, p. 315–328, doi:10.1130/GES00120.1.

Rubatto, D., 2002, Zircon trace element geochemistry: partitioning with garnet and the link between U-Pb age and metamorphism: Chemical Geology, v. 184, p. 123–138, doi:10.1016/S0009-2541(01)00355-2.

Schultz, M., Chacko, T., Heaman, L., Sanderman, H., Simonetti, A., and Creaser, R., 2007, Queen Maud block: A newly recognized Paleoproterozoic (2.4–2.5 Ga) terrane in northwest Laurentia: Geology, v. 35, p. 707–710, doi:10.1130/G23629A.1.

Sears, J., and Price, R., 2003, Tightening the Siberian connection to western Laurentia: Geological Society of America Bulletin, v. 115, p. 943–953, doi:10.1130/B25229.1.

Sears, J., Graff, P., and Holden, G., 1982, Tectonic evolution of lower Proterozoic rocks, Uinta Mountains, Utah and Colorado: Geological Society of America Bulletin, v. 93, p. 990–997, doi:10.1130/0016-7606(1982)93<990:TEOLPR>2.0.CO;2.

Shervais, J., 2006, Significance of Subduction-related Accretionary Complexes in Early Earth Processes, *in* Reimold, U., and Gibson, R., eds., Early Earth Processes: Geological Society of America Special Paper 405, p. 173–192.

Shufeldt, O., Karlstrom, K., Gehrels, G., and Howard, K., 2010, Archean detrital zircons in the Proterozoic Vishnu schist of the Grand Canyon, Arizona: Implications for crustal architecture and Nuna supercontinent reconstructions: Geology, v. 38, p. 1099–1102, doi:10.1130/G31335.1.

Spencer, C., Harris, R., and Dorais, M., 2009, Metamorphic conditions of the Little Willow complex, Utah and the implication for Utah's Proterozoic paleogeography: Geological Society of America Abstracts with Programs, v. 41, p. 44.

Strickland, A., Miller, E., and Wooden, J., 2011, The timing of Tertiary metamorphism and deformation in the Raft River-Albion-Grouse Creek core complex, Utah and Idaho: The Journal of Geology, v. 119, p. 185–206, doi:10.1086/658294.

Voice, P., Kowalewski, M., and Eriksson, K., 2011, Quantifying the timing and rate of crustal evolution: Global compilation of radiometrically dated detrital zircon grains: The Journal of Geology, v. 119, p. 109–126, doi:10.1086/658295.

Whitmeyer, S., and Karlstrom, K., 2007, Tectonic model for Proterozoic growth of North America: Geosphere, v. 3, p. 220–259, doi:10.1130/GES00055.1.

Wooden, J., and Dewitt, E., 1991, Pb isotopic evidence for the boundary between the early Proterozoic Mojave and Central Arizona Provinces in western North America, *in* Karlstrom, K., ed., Proterozoic Geology and Ore Deposits of Arizona: Arizona Geological Survey Digest, v. 19, p. 27–50.

Wooden, J., and Miller, D., 1990, Chronologic and isotopic framework for early Proterozoic crustal evolution in the eastern Mojave desert region, SE California: Journal of Geophysical Research, v. 95, p. 20,133–20,146, doi:10.1029/JB095iB12p20133.

Yonkee, A., Willis, G., and Doelling, H., 2000, Petrology and geologic history of the Precambrian Farmington Canyon complex, Antelope Island, Utah: Utah Geological Survey Miscellaneous Publication, v. 00–01, p. 5–36.

Zartman, R., 1974, Lead isotopic provinces in the Cordillera of the western United States and their geologic significance: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 69, p. 792–805, doi:10.2113/gsecongeo.69.6.792.

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