Age, provenance, and tectonic setting of Paleoproterozoic quartzite successions in the southwestern United States

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ABSTRACT

New field studies combined with U-Pb zircon geochronology constrain the ages of deposition and sedimentary provenance of Paleoproterozoic quartzite successions exposed in the southwestern United States. Orthoquartzites were deposited in short-lived basins at two times (ca. 1.70 and 1.65 Ga) during crustal assembly of southern Laurentia. The more voluminous ca. 1.70 Ga successions occur in southern Colorado, northern New Mexico, and central Arizona and are interpreted here to be time correlative, though not necessarily deposited in the same basins. Detrital zircon from quartzites and metaconglomerates exposed in southern Colorado and northern New Mexico is characterized by a single population with a relatively narrow range of ages (1.80–1.70 Ga) and minimal Archean input (<5% of grains analyzed). Peak detrital zircon ages (1.76–1.70 Ga) vary slightly from location to location and mimic the age of underlying basement. Unimodal detrital populations suggest local sources and a first-cycle origin of the orthoquartzites within a short time interval (1.70–1.68 Ga) during unroofing of local underlying basement. The maximum age of quartzite exposed at Blue Ridge, Colorado, is constrained by the 1705–1698 Ma coarse-grained granitoid basement on which quartzite was deposited unconformably. The minimum age of Ortega Formation quartzite (New Mexico) is constrained by ca. 1680–1670 Ma metamorphic monazite overgrowths. These dates agree with direct ages on the lower Mazatzal Group, Arizona, and suggest that orthoquartzite deposition occurred over a wide region during and soon after the ca. 1.70 Ga Yavapai orogeny. Regional structural arguments and the thrust style of quartzite deformation suggest that the metasedimentary successions were deformed during the ca. 1.66–1.60 Ga Mazatzal orogeny, thus making them important time markers separating the Yavapai and Mazatzal orogenic events.

Our model for syntectonic deposition involves extensional basin development followed by thrust closure, possibly due to opening and closing of slab rollback basins related to outboard subduction. The first-cycle origin of orthoquartzites near the end of the arc collisions of the Yavapai orogeny seems to contrast sharply with their extreme compositional maturity. This can be explained in terms of protracted, extreme diagenesis and/or special environmental influences that enhanced chemical weathering but were unique to the transitional atmosphere and ocean chemistry of the Proterozoic. Similarities among quartzites exposed throughout the southwestern United States and along the Laurentian margin suggest that they represent a widespread regional, and perhaps global, episode of sedimentation involving a distinctive syntectonic setting and unique climatic conditions, a combination that might make these units a signature lithology for Paleoproterozoic time.

Keywords: quartzite, Proterozoic, Colorado, New Mexico, U-Pb geochronology, detrital zircon, laser-ablation, ICP-MS.

INTRODUCTION

Successions of unusually thick and compositionally ultramature orthoquartzite are exposed throughout the southwestern United States and in many Paleoproterozoic orogens around the world (Fig. 1). These distinctive sequences were deposited ca. 1.70 Ga and have the potential to elucidate broad aspects of Proterozoic Earth systems. The quartzite and related rhyolite successions are emerging as key tectonic marker units for distinguishing the timing and character of events that resulted in growth and stabilization of continental lithosphere in the southwestern United States (Karlstrom and Bowring, 1988; Hoffman, 1988; Jessup et al., 2006). The primary goal of this paper is to show that new depositional ages and provenance studies of quartzites exposed in Colorado and New Mexico can help to refine regional tectonic models for the growth of Laurentia by showing a close temporal association among regional orogenesis, quartzite deposition, and their subsequent deformation.

Thick successions of orthoquartzite and interlayered schist are exposed in each of the major Proterozoic crustal provinces of the southwestern United States (Fig. 1), but the age and tectonic setting of these metasedimentary rocks have not been well understood. Absolute ages are only available for a small number of localities, and the limited geographical extent of quartzite exposures complicates the cor-

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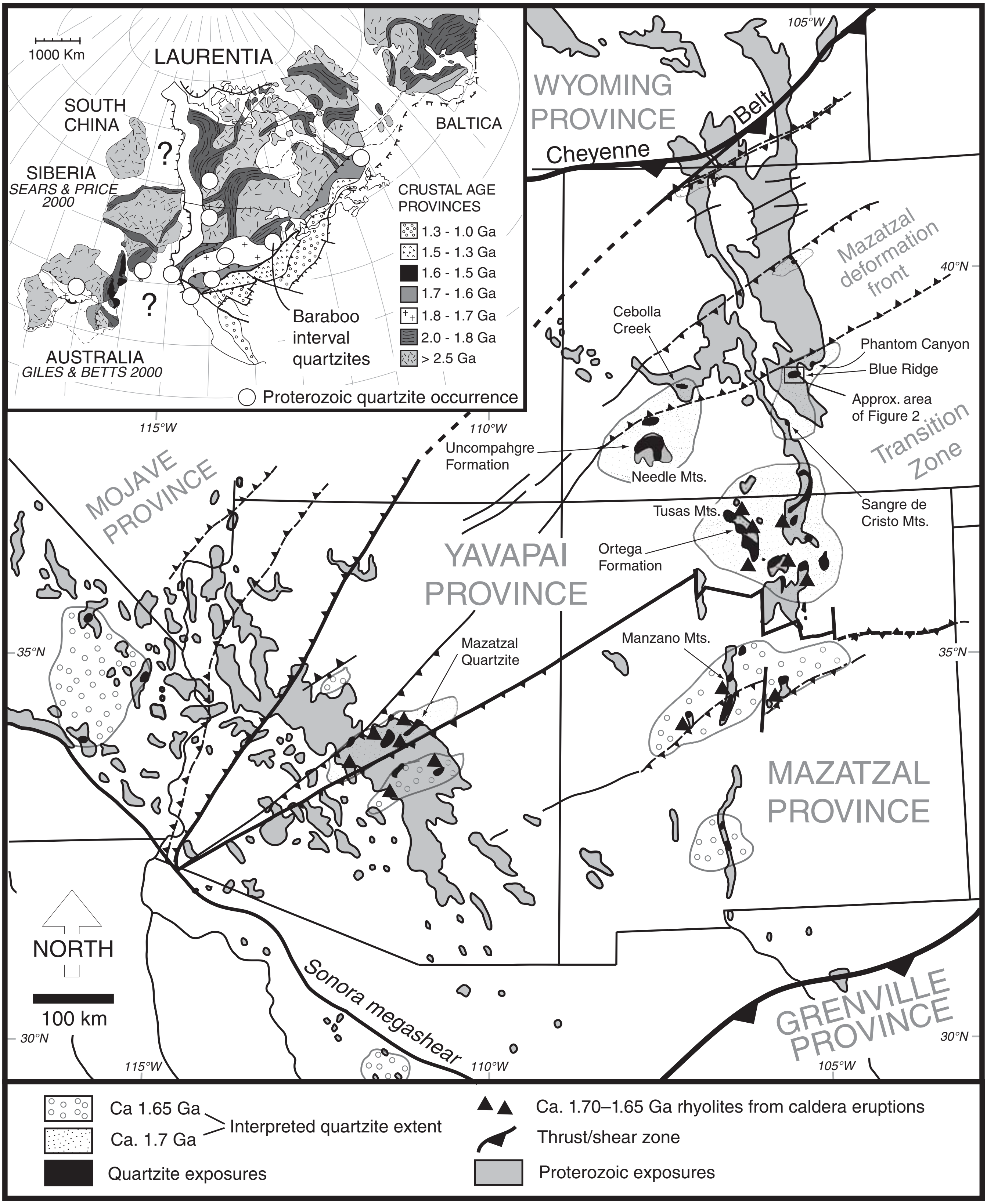

Figure 1. Paleoproterozoic quartzites of southwestern Laurentia. Inset shows possible western Rodinian continents and global Proterozoic quartzite occurrences (relative positions all uncertain; modified from Karlstrom et al., 2001; Sears and Price, 2000; Giles and Betts, 2000). Quartzite localities mentioned in text are labeled accordingly. Faults shown without thrust teeth are either inferred thrust faults or strike-slip faults. The outlines of possible depocenters are inferred and are discussed in the text.

relation of the successions at the regional and global scale. In this paper, we examine Rocky Mountain examples in the context of a model for short-lived syntectonic basins that opened and closed within the upper plate of subduction systems during slab rollback (Giles et al., 2002). New data in support of this model come from U-Pb geochronology, which constrains the depositional age and provenance of quartzite successions exposed in Colorado and New Mexico (Fig. 1). New field mapping and observations are integrated with U-Pb zircon geochronology on underlying, interlayered, and crosscutting igneous bodies in southern Colorado to investigate the timing of sedimentation, deformation, and metamorphism. A detrital zircon study using laser-ablation (LA) inductively-coupled-plasma mass spectrometry (ICP-MS) techniques adds additional depositional age constraints and provides new insights into the provenance of quartzite and metaconglomerates in these distinctive metasedimentary successions.

We also discuss Paleoproterozoic orthoquartzites as potential secular markers that will be useful for understanding Proterozoic tectonics and climatic conditions. Orthoquartzite successions may provide an important tool for correlating Proterozoic rocks around the world and, thus, might be used to test proposed contiguous plate margins of ancient supercontinents (Hoffman, 1988; Karlstrom et al., 2001; Rogers, 1996; Sears and Price, 2003). The contrast between the compositional maturity of quartzites and their juvenile detrital character seemingly requires protracted diagenesis and/or extreme chemical weathering prior to and during deposition. The Proterozoic represents a critical time in the evolution of Earth's ocean-atmosphere system as it transitioned from a CO_2-H_2S–dominated system to one of excess oxygen (Canfield et al., 2000; Canfield and Teske, 1996), ultimately setting the stage for the explosion of life at the end of the Precambrian. This transition is commonly thought to have resulted in the disappearance of banded iron formation and the complementary appearance of red sandstones and shales through the late Paleoproterozoic to early Mesoproterozoic (Holland, 1984; Canfield, 1998). The appearance of thick Paleoproterozoic quartzites in other parts of southern Laurentia during this transition is attributed to distinctive Proterozoic weathering conditions (e.g., Medaris et al., 2003) involving some combination of (1) high CO_2 and CH_4 and low pH coupled with the absence of stabilizing plants, (2) presence of microbial mats (Dott, 2003), (3) depositional conditions involving extreme wind and water abrasion (Dott, 2003), and/or (4) diagenetic conditions involving the breakdown and removal of labile materials (Cox et al., 2002a). We briefly examine possible correlations between Paleoproterozoic quartzite successions throughout southern Laurentia in light of new age constraints presented herein and suggest that orthoquartzite deposition may be a widespread but temporally restricted phenomenon and, thus, a signature event in Earth history.

GEOLOGIC BACKGROUND

The core of Laurentia is composed of Archean crustal provinces that were assembled across Early Proterozoic mobile belts between ca. 2.0 and 1.8 Ga (Hoffman, 1988). Following the assembly of its cratonic core, Laurentia subsequently underwent a period of southward growth from 1.8 to 1.6 Ga, during which much of the Precambrian continental lithosphere of the southwestern United States was formed (Whitmeyer and Karlstrom, 2007). Proterozoic exposures in the southwestern United States have been divided into several crustal provinces based on rock ages and isotopic characteristics (Fig. 1). The Yavapai Province is interpreted to represent a complex collage of predominantly juvenile arc terranes characterized by rocks with Nd model ages between 2.0 and 1.8 Ga (Bennett and DePaolo, 1987). Rocks of the Yavapai Province were accreted south of the Archean Wyoming Province between 1.78 and 1.70 Ga via assembly of volcanic arc terranes in a belt stretching from Colorado to Arizona. The final collisional phase of this long-lived, progressive orogenic event (Yavapai orogeny) occurred between ca. 1.71 and 1.70 Ga and is interpreted as the welding of arc terranes to Laurentia (Karlstrom and Bowring, 1988; Whitmeyer and Karlstrom, 2007). This orogenic peak was followed by a prolonged episode of voluminous "postorogenic" granitoid magmatism from 1.70 to 1.66 Ga (Anderson and Cullers, 1999).

The Mazatzal Province lies to the south of the Yavapai Province and extends across central and southern New Mexico and Arizona. Mazatzal Province rocks are characterized by Nd model ages between 1.8 and 1.7 Ga (Bennett and DePaolo, 1987), and they were accreted to the southern Yavapai Province during the 1.66–1.60 Ga Mazatzal orogeny (Silver, 1965; Karlstrom and Bowring, 1988; Luther, 2006; Amato et al., 2008). Mazatzal-aged deformation affected a large foreland region of the southern Yavapai Province (transition zone, Fig. 1; Karlstrom and Humphreys, 1998), and the Mazatzal deformation front represents the approximate northern extent of these effects (Shaw and Karlstrom, 1999). After an ~150 m.y. tectonic lull, renewed southward growth of Laurentia is inferred to have occurred during the Mesoproterozoic. Reactivation of the Paleoproterozoic lithosphere accompanied a widespread regional pulse of A-type granitic magmatism between 1.45 and 1.36 Ga (Reed et al., 1993), possibly in response to renewed crustal accretion along a distal southern margin (Nyman et al., 1994; Whitmeyer and Karlstrom, 2007). These events were all part of a prolonged, ~800 m.y. episode of crustal growth along southern Laurentia along a long-lived "southern" plate margin that culminated in the Grenville orogeny and assembly of the supercontinent Rodinia at ca. 1.1 Ga (Karlstrom et al., 2001).

During the southward growth of Laurentia, thick (1–2 km) successions of quartz sandstone were deposited within the orogenic belts. Some of the best examples of these deposits are exposed in the Lake Superior region of the northern United States (Baraboo interval; Dott, 1983) and throughout the southwestern United States (Fig. 1). Quartzite successions occur in the Yavapai, Mazatzal, and Mojave Provinces (Fig. 1), and exposures include extensively exposed units like the Ortega Formation (New Mexico), Mazatzal quartzite (Arizona), and Uncompahgre Formation (Colorado) as well as numerous smaller, more localized exposures having similar lithologies and outcrop characteristics. Existing age constraints suggest that sedimentation occurred generally after the Yavapai orogeny and before the Mazatzal orogeny (Jones and Connelly, 2006; Jessup et al., 2006). Quartzite successions are commonly nearly pure (>95%) quartz with minor muscovite, Al-silicates, hematite, zircon, and monazite. Primary sedimentary structures are locally well preserved, including common cross-stratification. Depositional facies are similar from bottom to top and region to region and indicate shallow-marine (<10 m water depth) or fluvial environments (Harris and Eriksson, 1990; Soegaard and Eriksson, 1985, 1989; Trevena, 1979). Across much of the southwestern United States, quartzites directly overlie thick successions of voluminous, high-silica rhyolite (Fig. 1). The contact between rhyolite and quartzite is generally interlayered to gradational and is commonly marked by a distinctive, Mn-rich contact interval (Bauer and Williams, 1989). In quartzite successions exposed in New Mexico and Arizona, U-Pb ages of interlayered rhyolite locally constrain the onset of quartzite deposition at 1701 ± 2 Ma (e.g., Cox et al., 2002b). In southern Colorado, however, rhyolite is notably absent. Quartzites are typically underlain by pebble to cobble conglomerates up to a few meters thick, and these conglomerates contain a variety of clast compositions, including vein quartz, quartzite, jasper, chert, and, locally, granite (Barker, 1969; Reuss, 1974). Although clast compositions do not always reflect the local makeup of underlying basement assemblages, the uppermost part of the basement is locally marked by a zone of deep weathering (regolith), which is interpreted to have developed prior to the onset of quartzite sedimentation.

Basement rock assemblages underlying quartzite-rhyolite successions regionally are typically characterized by metamorphosed mafic volcanic rocks and volcanogenic marine metasedimentary rocks (Bauer and Williams, 1989; Jessup et al., 2005). Examples of these older (1.80–1.72 Ga; Condie, 1982) assemblages include the Moppin Complex in northern New Mexico (Bauer and Williams, 1989) and the Dubois and Cochetopa successions in southern Colorado (Bickford and Boardman, 1984). Basement rocks commonly contain evidence for multiple episodes of deformation and/or metamorphism that are not recognized in the overlying quartzite (Gibson and Harris, 1992). Thus, the contact between basement assemblages and quartzite successions has been variably interpreted as an unconformable depositional contact, a sheared unconformity, or a fault contact.

The quartzite-rhyolite successions and underlying basement assemblages have been deformed by folding and thrust imbrication. Across Colorado, quartzite exposures presently occur as tight, upright synclinal "keels," which are interpreted to be the roots of larger, now-eroded folds (Fig. 2; Reuss, 1974; Wells et al., 1964). In the Needle Mountains of southwestern Colorado, the Tusas Mountains of northern New Mexico, and the Mazatzal Mountains of Arizona, 1–2-km-thick sections of quartzite define tight to open, large-wavelength (kilometer scale) folds consistent with some fold-and-thrust-belt geometries (Harris, 1990; Williams, 1991; Williams et al., 1999). The quartzites were buried to depths up to 10–15 km and subsequently resided at these mid-crustal depths until at least ca. 1.4 Ga, when they were widely intruded by coarse-grained granitic plutons. Whereas published absolute age constraints from quartzite successions exposed in the Yavapai and Mazatzal Provinces indicate that sedimentation occurred during the Paleoproterozoic (Bauer and Williams, 1989; Cox et al., 2002b; Shastri, 1993), the minimum depositional age is poorly constrained because crosscutting igneous bodies generally yield ages of ca. 1.4 Ga and, hence, do not provide sufficient restrictions on the age of deposition or of deformation (Harris et al., 1987).

BLUE RIDGE, COLORADO, QUARTZITE SUCCESSION

Proterozoic quartzite, schist, and conglomerate are exposed in a northeast-trending, tight, upright syncline along Blue Ridge (Fig. 2), ~10 km north-northwest of Cañon City, Colorado. The metasedimentary succession is in contact with coarse-grained, foliated to locally mylonitic granodiorite and is cut by numerous pegmatite dikes. This area was chosen for new geochronologic study to determine the age of quartzite deposition and deformation in the southern Yavapai Province. The metasedimentary succession exposed along Blue Ridge is representative of similar successions exposed elsewhere in Colorado that lack underlying or interlayered metavolcanic rocks. Detailed descriptions of the characteristic lithologies and structural elements observed in outcrops at Blue Ridge can be found in the GSA Data Repository.[1] New U-Pb zircon results from granitoids that underlie and crosscut the quartzite succession are described next.

U-Pb Geochronology

Four samples were collected for new U-Pb geochronology to constrain the age of quartzite deposition and deformation. Samples included foliated granodiorite exposed north of the quartzite succession, strongly deformed granodiorite from the southern, sheared contact, and two pegmatite dikes that crosscut the folded succession and sheared granodiorite (see Fig. 2A for locations). Basal conglomerate and quartzite located 10 m higher in the stratigraphic section were also sampled as part of the detrital zircon study described here. U-Pb isotopic data and sample location coordinates are available from the GSA Data Repository (Table DR1, see footnote 1), and concordia diagrams are presented in Figure 3. Analytical methods followed those of Jones and Connelly (2006). Zircon fractions were handpicked, examined using a petrographic microscope, characterized by cathodoluminescence, extensively abraded (Krogh, 1982), and then subjected to a final optical reevaluation before analysis.

Foliated Granodiorite (J01-BR3)

A sample of weakly foliated, coarse-grained granodiorite mapped as part of the Paleoproterozoic Twin Mountain batholith was collected 5 km to the north of Blue Ridge along Fremont County Road 69 (Fig. 2A). Locally, this sample represents granitoid basement interpreted to unconformably underlie the quartzite succession, and it was collected to determine the maximum age for quartzite deposition. The sample yielded a single population of colorless to light tan, euhedral to subhedral, equant to slightly elongate prismatic zircon typical of an igneous origin. Three fractions (Z1–Z3) define a line with intercepts of 1706 +5/–3 Ma and 476 ± 276 Ma (Fig. 3A). The upper intercept is interpreted to represent the crystallization age of the granodiorite and is consistent with published ages of similar intrusive phases from elsewhere within the surrounding Twin Mountain and Crampton Mountain batholiths (1706 ± 5 Ma and 1705 ± 8 Ma, respectively; Bickford et al., 1989a). The lower intercept is interpreted to reflect more recent Pb loss.

Sheared Granodiorite (K00-BR-25)

Strongly foliated to locally mylonitic, coarse-grained granodiorite was sampled from the southern contact of the Gooseberry Gulch syncline (Fig. 2A). Although the nature of the original contact between the quartzite succession and granodiorite is ambiguous at this location due to shear-zone development, this sample was collected to correlate the age of basement granitoids on both sides of the folded quartzite succession. This sample yielded a single population of colorless to light tan, equant, euhedral to subhedral prismatic grains typical of an igneous origin. The four fractions analyzed all plot near concordia and have $^{207}Pb/^{206}Pb$ ages ranging from 1708 to 1693 Ma (Table DR1, see footnote 1). Three fractions (Z2–Z4) plot along a reference line with intercepts of 1698 Ma and 0 Ma (Fig. 3B). The upper intercept of this line corresponds to the average $^{207}Pb/^{206}Pb$ age of 1698 ± 4 Ma for the three fractions and is interpreted to represent the crystallization age of the granodiorite. The fourth fraction (Z1) plots slightly below the reference line and is interpreted to contain inherited zircon. The age of this sample overlaps within error the age of granodiorite north of Blue Ridge (sample J01-BR3) and with published ages for the Twin Mountain and Crampton Mountain batholiths, suggesting that the southern contact of the quartzite succession might have originally been an unconformable depositional contact.

Crosscutting Pegmatite Dikes (K00-BR-26 and J03-BR4)

Two pegmatite dikes that crosscut the southern limb of the folded quartzite succession and the sheared granodiorite were sampled to constrain the age of deformation locally. Sample K00-BR-26 was collected from of a suite of subplanar, steeply dipping to vertical intrusions that are commonly thin (<0.5 m) but can be, locally, up to a few meters thick. Sample J03-BR4 was collected from a pink to red, thin (30 cm) pegmatite dike that cuts the sheared granodiorite

[1]GSA Data Repository Item 2008213, containing detailed rock descriptions and complete U-Pb isotopic data, is available at www.geosociety.org/pubs/ft2008.htm. Requests may also be sent to editing@geosociety.org.

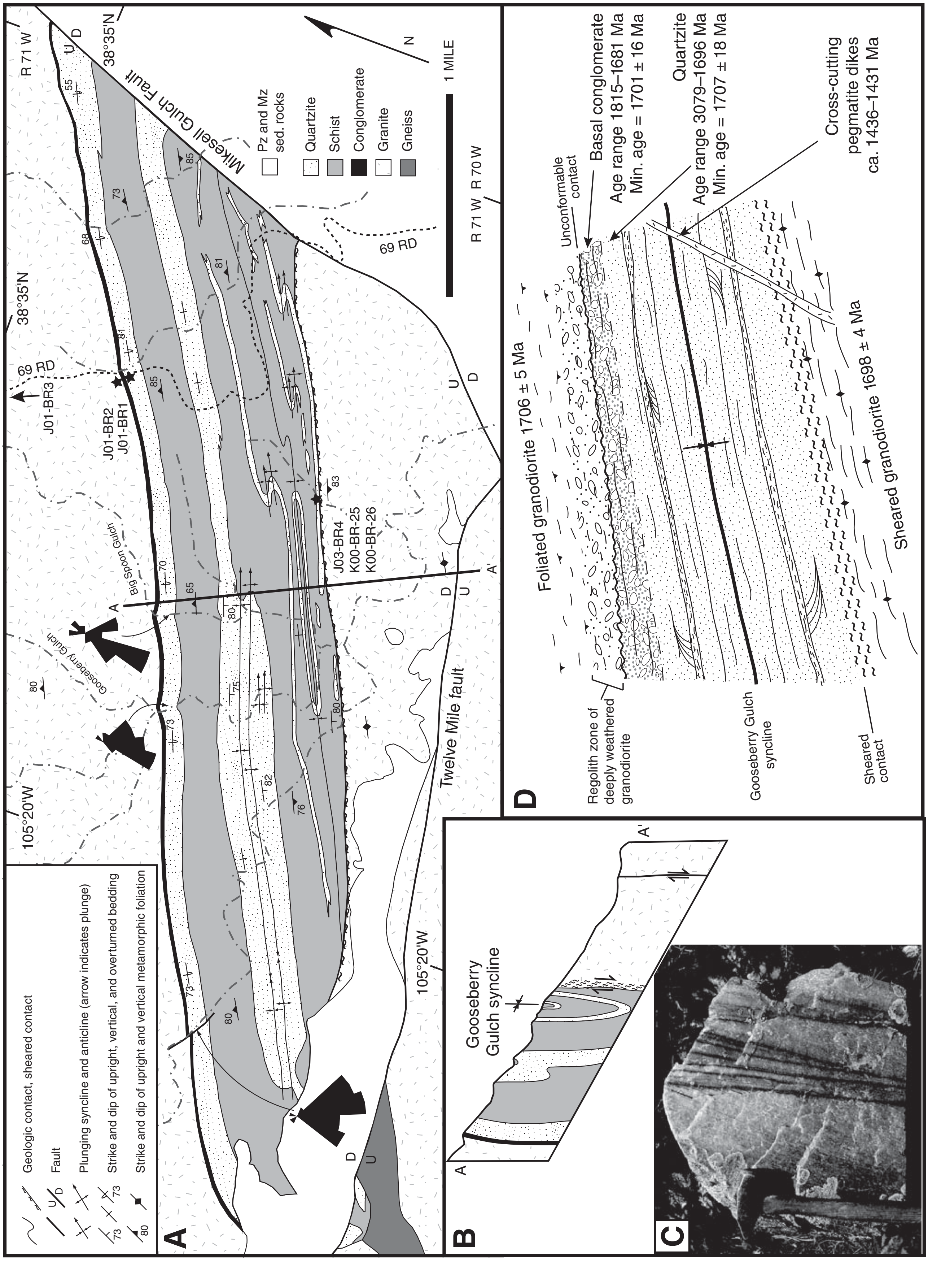

Figure 2. Geology of the Blue Ridge area, Colorado. (A) Generalized geologic map of the Proterozoic metasedimentary succession exposed along Blue Ridge, Colorado (after Reuss, 1970, 1974). Locations of geochronology samples are indicated by stars. Paleocurrent data from lower quartzite unit are from Reuss (1974). (B) Schematic geologic cross section across Gooseberry Gulch syncline (from Reuss, 1970, 1974). (C) Field photograph of block of quartzite bedrock from north side of syncline near J01-BR1 sample locality. (D) Schematic diagram (not to scale) of interpreted crosscutting relationships and summary of new U-Pb igneous crystallization and detrital zircon ages.

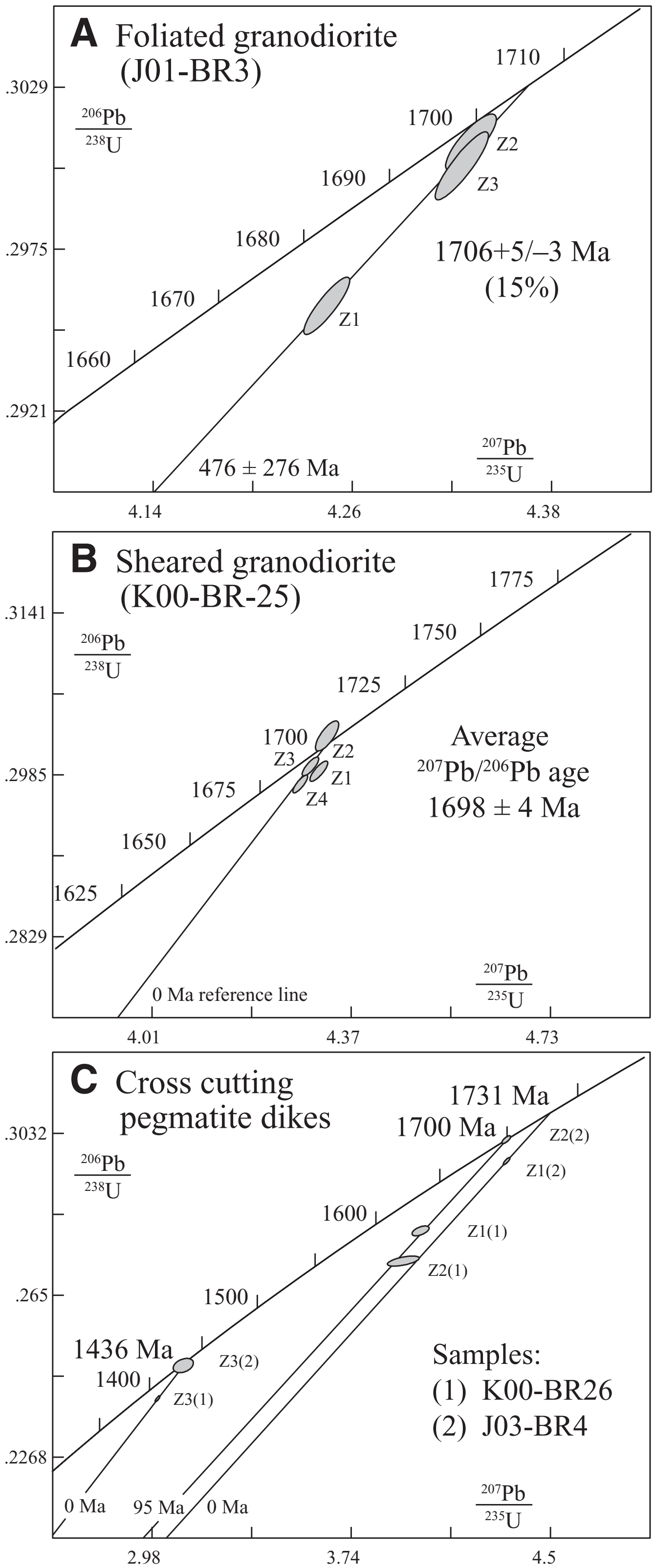

Figure 3. U-Pb concordia diagrams for samples from Blue Ridge, Colorado. Ages were determined by linear regression through the data except where indicated, and probability of fit (%) is indicated in parentheses. For complete data set, see GSA Data Repository Table DR1 (see text footnote 1).

and quartzite fabric but also locally deflects foliation in quartzose schist. Both samples yielded a single population of light pink to colorless, euhedral to subhedral prismatic zircon typical of an igneous origin. Some zircon fractions have $^{207}Pb/^{206}Pb$ ages of ca. 1700 Ma or older (Fig. 3C; Table DR1 [see footnote 1]), which are attributed to inheritance from host-rock granodiorite and/or quartzite. Two fractions, one of which was concordant, have $^{207}Pb/^{206}Pb$ ages of ca. 1436 Ma (Fig. 3C; Table DR1 [see footnote 1]). This age is interpreted as the crystallization age of the pegmatites, indicating that they formed coeval with a well-documented regional suite of granites and related pegmatite dikes emplaced ca. 1440–1430 Ma (Reed et al., 1993; Karlstrom et al., 2004).

QUARTZITE DETRITAL ZIRCON GEOCHRONOLOGY

A suite of Paleoproterozoic quartzites was collected for U-Pb detrital zircon study using laser-ablation–inductively-coupled-plasma mass spectrometry (LA-ICP-MS) techniques to constrain the maximum age of quartzite deposition and to characterize the sedimentary provenance of the successions. Ten samples were collected from exposures in the Yavapai Province of southern Colorado and northern New Mexico (Fig. 1). Samples were collected from thick, extensively exposed units (Ortega Formation and Uncompahgre Formation) and smaller, more localized occurrences (e.g., Cebolla Creek, Blue Ridge, and Phantom Canyon localities). In most cases, representative samples of quartzite or basal conglomerate were collected from the stratigraphically lowest part of the exposed section. At two localities, samples were collected from different stratigraphic horizons to investigate the evolution of the detrital zircon population(s) during the depositional history of the successions. Samples of basal conglomerate and quartzite from 10 m higher in the stratigraphic section were collected from exposures along Blue Ridge, Colorado (Fig. 2). In the Needle Mountains, Colorado, samples of the Uncompahgre Formation were collected from the basal conglomerate and from the lower and upper parts of the 300-m-thick Q4 quartzite unit, >2 km higher in the stratigraphic section (Harris and Eriksson, 1990). One sample was also collected from the Vallecito Conglomerate, a unit that was recently interpreted to lie stratigraphically beneath the Uncompahgre Formation (Zinsser, 2006; Zinsser and Karlstrom, 2006).

Sample preparation techniques and analytical methods followed those described in Jones and Connelly (2006). Zircon from the least magnetic fraction was handpicked to include grain populations representing each of the various morphologies, sizes, and colors that were recognized. Approximately 100 grains from each sample were analyzed, and age distribution plots and U-Pb concordia diagrams are shown in Figure 4. Detrital zircon ages are summarized in Table 1, and complete data tables are available in the GSA Data Repository (Table DR3, see footnote 1). The estimated uncertainty (i.e., external reproducibility) of each individual analysis was ~50 m.y. (~3%). Peak and minimum detrital ages were calculated using only grains that were determined to be <3% discordant. The minimum age reported for each sample (Table 1) represents the weighted average of the youngest cluster of concordant grains with overlapping ages.

Results

Zircon morphologies were highly variable among all of the samples and ranged from euhedral and prismatic to well rounded and lightly frosted. In general, rounded and frosted or pitted grains were rare. Subhedral to euhedral prismatic zircon morphologies were most common, suggesting minimal transport and derivation of sediment from dominantly igneous source rocks. The range of detrital zircon $^{207}Pb/^{206}Pb$ ages among all samples was 3079–1657 Ma (Table 1), but all of the samples were primarily characterized by Paleoproterozoic-aged detritus (Fig. 4). The range of Paleoproterozoic detrital zircon ages was 1973–1657 Ma (Table 1), and the detrital zircon was dominated in most cases by grains with ages between ca. 1800 and 1700 Ma (Fig. 4). Archean-aged zircon was present in six of the ten samples but was relatively minor in all cases (<5% of grains analyzed). Peak detrital ages define a narrow range of 1762–1702 Ma (Table 1), and the mode for each sample locality closely matched published U-Pb zircon ages of surrounding basement assemblages (Reed et al., 1993; Karlstrom et al., 2004), as discussed further later.

The detrital zircon populations do not appear to change significantly in both cases where samples were collected from different stratigraphic horizons within the same succession. In two samples from exposures along Blue Ridge, Colorado, basal conglomerate is characterized by a relatively restricted Paleoproterozoic detrital age population (1815–1681 Ma; Fig. 4O), whereas quartzite 10 m upsection is characterized by a broader age range, including Archean material (3079–1696 Ma; Fig. 4M). The peak detrital zircon ages for the basal conglomerate and quartzite were 1722 Ma and 1734 Ma, respectively (Table 1). In four samples from the Needle Mountains, Colorado, there is noticeable change in the detrital zircon population from the Vallecito Conglomerate to the basal conglomerate and Q4 quartzite of the Uncompahgre Formation (Fig. 5). Samples from higher in the stratigraphic section yielded a larger range of detrital zircon ages, and the upper quartzite (Q4) contains a distinct population of ca. 1880 Ma detrital grains not recognized in the other samples. All of the samples are dominated by a single population of Paleoproterozoic-aged detritus, though, and the peak ages do not vary significantly.

Figures 5–7 show age distribution plots of the Proterozoic detrital zircon for each sample and U-Pb crystallization ages of the basement underlying the quartzites in the different outcrop areas. In the Uncompahgre Group, basement consists of the 1810–1780 Ma Irving Formation and 1772–1754 Ma Twilight Gneiss, all intruded before quartzite deposition by the 1735–1715 Ma Tenmile granite and the ca. 1700 Ma Bakers Bridge Granite (Gonzales and Van Schmus, 2007). The detrital zircon age range (1800–1700 Ma) and mode (1740–1760 Ma) represent a remarkably good average of these local basement ages, and these dominant populations persist throughout the >2.5-km-thick succession. Similarly, quartzite exposed along Cebolla Creek has a mode (1756 Ma) similar to its underlying Dubois Formation basement (Figs. 6A and 6B); the Ortega Formation quartzite peak at 1723 Ma reflects its ca. 1760–1720 Ma metavolcanic basement as well as ca. 1700 Ma underlying rhyolite (Figs. 6C and 6D; Karlstrom et al., 2004); and quartzite exposed in the Sangre de Cristo Mountains and along Blue Ridge and Phantom Canyon have detrital zircon age ranges and peak ages that reflect ca. 1750–1690 Ma basement ages in the Salida and Cañon City region of Colorado (Fig. 7; Bickford et al., 1989a, 1989b).

The youngest concordant detrital zircon grains yielded an averaged age range of 1733–1700 Ma for all samples. The youngest averaged age of 1700 ± 18 Ma (sample J03-PC1, Table 1) was from a 200-m-thick band of quartzite exposed in Phantom Canyon (Wobus et al., 1985), ~20 km northeast of Cañon City, Colorado. Three of the youngest detrital zircon grains from this sample were reanalyzed by more precise isotope-dilution techniques, which gave a regressed U-Pb age of 1701 ± 3 Ma (Fig. 8; Table DR2 [see footnote 1]), confirming the minimum age calculated from the LA-ICP-MS data. A 100-m-thick band of quartzite exposed in the central Sangre de Cristo Mountains, southern Colorado (sample J02-MP4; Jones and Connelly, 2006), contained the largest population of young (i.e., ca. 1700 Ma or younger) grains (Fig. 4Q), and the weighted average of 68 concordant to near-concordant analyses with overlapping ages (within error) was 1702 ± 6 Ma (Table 1). Three samples had minimum detrital ages that were slightly older than the others (1730–1725 Ma, Table 1), and these samples were also characterized by slightly older peak ages. Otherwise, the distribution of detrital ages looks similar among all samples analyzed.

DISCUSSION

New geochronology and field observations reported here provide new constraints on the deposition, deformation, and metamorphism of quartzite successions exposed in the Yavapai Province of Colorado and northern New Mexico. These constraints are consistent with published age constraints on quartzite successions from elsewhere across the southwestern United States and North America and suggest that Proterozoic quartzites represent a widespread regional depositional event that closely followed the culmination of the Yavapai orogeny at ca. 1700 Ma. Detrital zircon data provide new insights into sources for the quartzite protoliths and the evolution of the depositional systems through time.

Quartzite Depositional Age

New geochronology from exposures along Blue Ridge, Colorado, reveals that granitoid basement underlying the metasedimentary succession at this locality crystallized at 1706 ± 5 Ma (Fig. 3). The presence of granodiorite "regolith" just beneath the metasedimentary succession is interpreted to represent rapid unroofing and weathering of the plutonic rocks prior to the onset of sedimentation. The gradational transition from regolith to phyllitic conglomerate that defines the base of the succession is interpreted to represent an unconformable depositional contact. Thus, 1706 ± 5 Ma is interpreted to represent a robust maximum age for the deposition of quartzite locally. The youngest detrital zircon from basal conglomerate and quartzite higher in the succession exposed along Blue Ridge yielded averaged ages of 1701 ± 16 Ma and 1707 ± 18 Ma, respectively (Table 1), which also provide maximum ages for deposition. Our best estimate for the maximum quartzite depositional age based on detrital zircon data is 1701 ± 3 Ma, the minimum age of detrital zircon from quartzite exposed in Phantom Canyon (see previous). This age is supported by detrital zircon data from exposures throughout the region, and slightly older minimum ages for a few samples are interpreted to represent the youngest material present in the source area rather than an older depositional age for the quartzite successions.

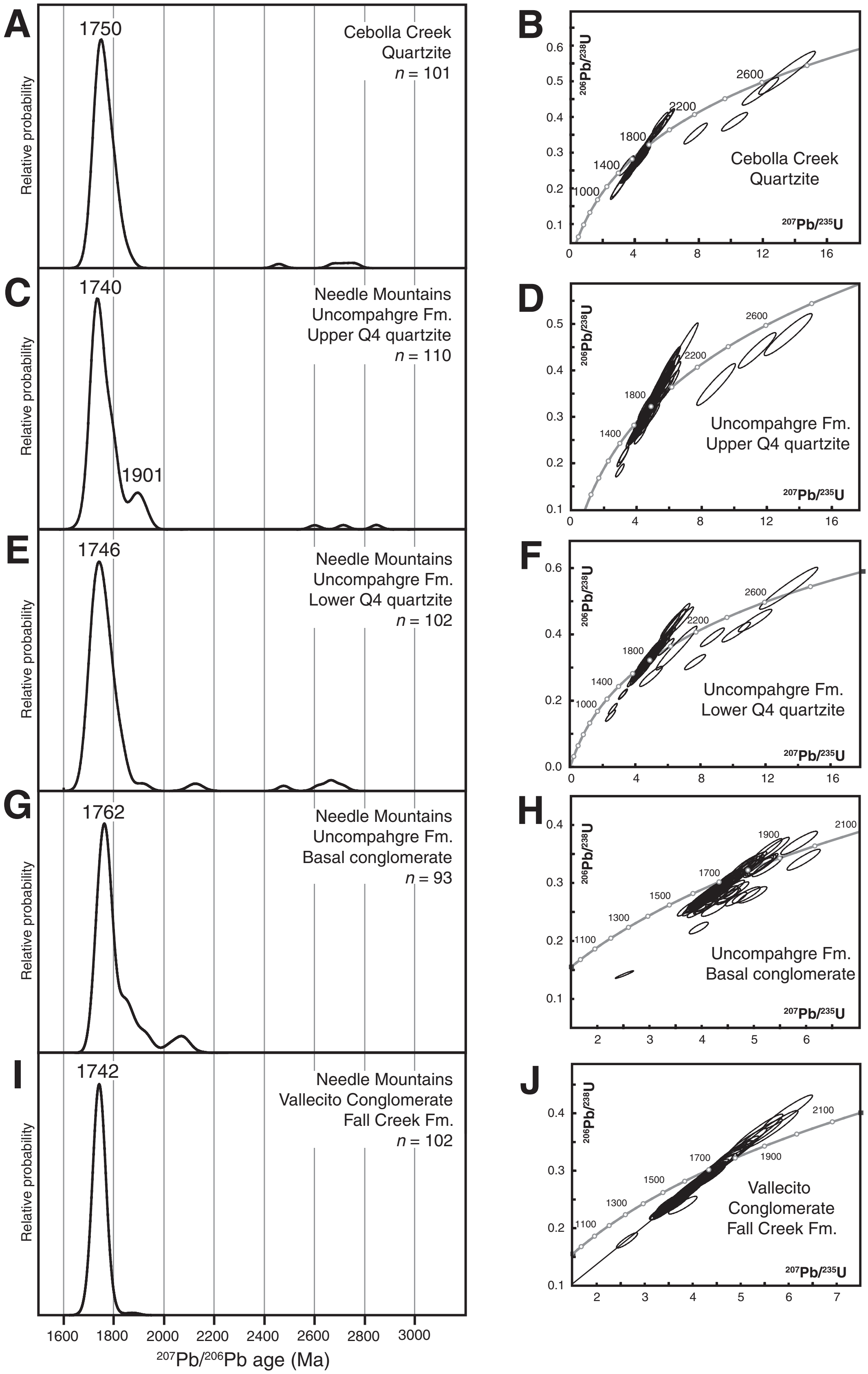

Figure 4. Relative probability diagrams for $^{207}Pb/^{206}Pb$ ages and U-Pb concordia diagrams for detrital zircon in Paleoproterozoic quartzites and metaconglomerates exposed in southern Colorado and northern New Mexico. Plots represent all grains analyzed, and ages of significant peaks are indicated. See Table 1 for a summary of all ages, and see Figures 5–7 for plots of nearly concordant (≤3%) Paleoproterozoic grains only. For complete data set, see GSA Data Repository Table DR3 (see text footnote 1). (*Continued on following page*.)

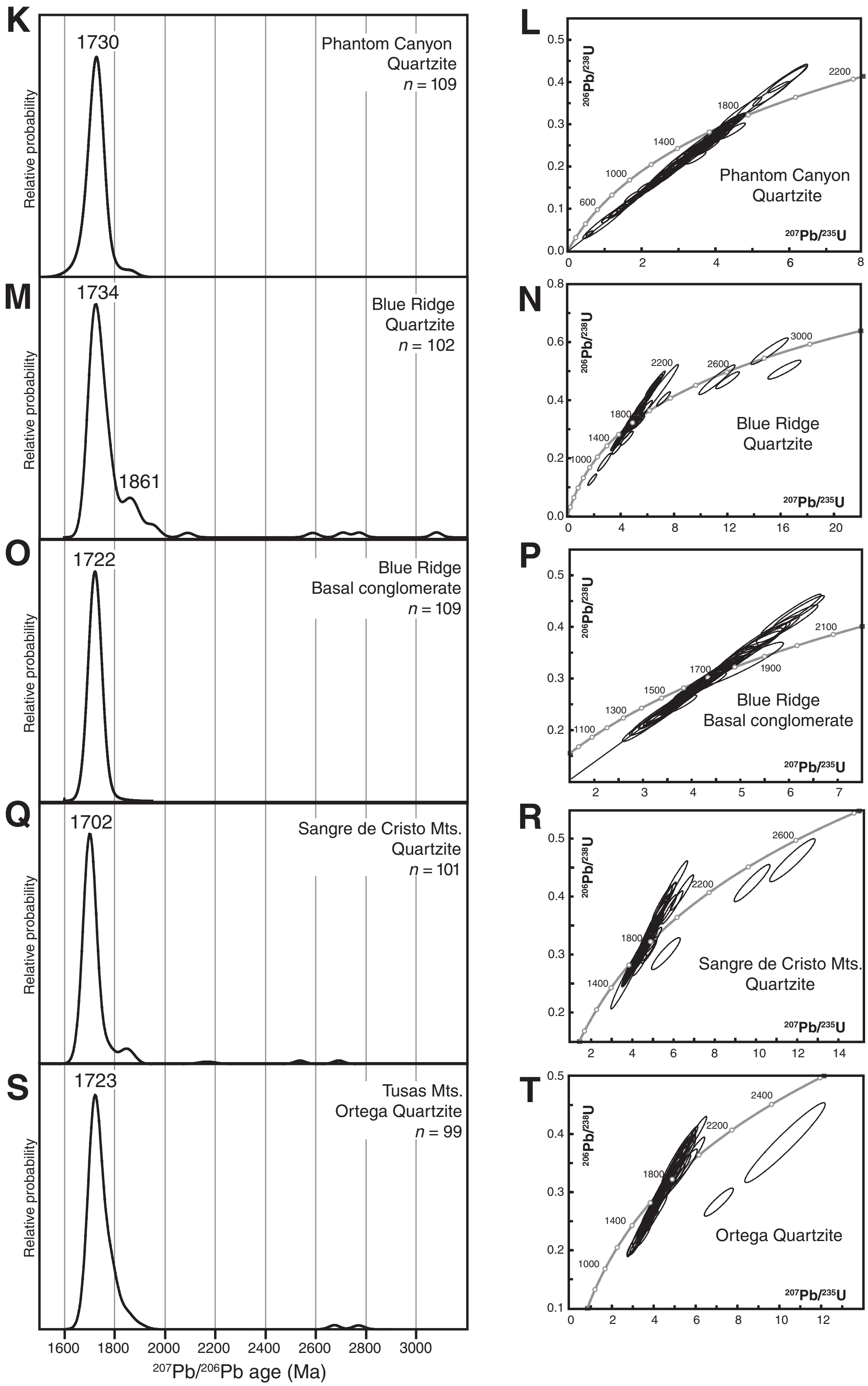

Figure 4 (*continued*).

TABLE 1. QUARTZITE DETRITAL ZIRCON AGE SUMMARY

Sample	Population	n	Unweighted age (Ma) Avg.	±	%	Median (peak) age (Ma) Avg.	±	%	$^{207}Pb/^{206}Pb$ age range
Phantom Canyon, Colorado									
J03-PC1	All	109	1726	7	0.38	1727	5	0.28	1869–1605 Ma
	<3% disc.	23	1727	10	0.58	1730	5/7	0.32	1754–1686 Ma
	Minimum age: 1700 ± 18 Ma (*n* = 8)								
Blue Ridge, Colorado									
J01-BR1	All	102	1816	48	2.6	1737	15/10	0.70	3079–1696 Ma
	<3% disc.	76	1760	14	0.78	1734	22/10	0.92	1955–1696 Ma
	Minimum age: 1707 ± 18 Ma (*n* = 8)								
J01-BR2	All	109	1722	5	0.28	1723	2	0.084	1815–1681 Ma
	<3% disc.	72	1721	6	0.34	1722	3	0.14	1815–1681 Ma
	Minimum age: 1701 ± 16 Ma (*n* = 9)								
Sangre de Cristo Mountains, Colorado									
J02-MP4	All	101	1740	30	1.70	1702	4/3	0.19	2694–1657 Ma
	<3% disc.	90	1715	8.5	0.50	1702	3	0.19	1869–1664 Ma
	Regressed U-Pb age (<1.8 Ga) = 1702 ± 6 Ma (MSWD = 0.17, li = 38 ± 150 Ma)								
	Minimum age: 1702 ± 6 Ma (*n* = 68)								
Tusas Mountains, New Mexico—Ortega Quartzite									
ORT-N	All	98	1767	32	1.80	1726	7/4	0.31	2771–1688 Ma
	<3% disc.	64	1735	10	0.56	1723	5/3	0.21	1904–1688 Ma
	Minimum age: 1704 ± 17 Ma (*n* = 9)								
Cebolla Creek, south of Gunnison, Colorado									
LC-CC-15	All	101	1805	39	2.10	1754	5/8	0.40	2760–1705 Ma
	<3% disc.	39	1756	9	0.53	1750	6/7	0.37	1834–1717 Ma
	Minimum age: 1725 ± 15 Ma (*n* = 11)								
Needle Mountains, Colorado—Uncompahgre Formation									
Q4 upper	All	110	1802	35	1.90	1746	13/9	0.63	2846–1671 Ma
	<3% disc.	91	1763	11	0.63	1740	13/5	0.54	1932–1671 Ma
	Minimum age: 1713 ± 16 Ma (*n* = 10)								
Q4 lower	All	102	1816	43	2.40	1752	10	0.53	2711–1687 Ma
	<3% disc.	84	1755	9	0.52	1746	13/7	0.58	1925–1687 Ma
	Minimum age: 1709 ± 15 Ma (*n* = 10)								
J03-NM4	All	88	1797	17	0.92	1769	10/6	0.43	2086–1723 Ma
	<3% disc.	58	1768	10	0.54	1762	9/12	0.59	1897–1727 Ma
	Minimum age: 1730 ± 16 Ma (*n* = 8)								
Needle Mountains, Colorado—Vallecito Conglomerate (Fall Creek Formation)									
J05-VC2	All	102	1744	5	0.27	1742	3/2	0.13	1795–1729 Ma
	<3% disc.	40	1745	8	0.43	1742	5/2	0.20	1795–1729 Ma
	Minimum age: 1733 ± 16 Ma (*n* = 9)								

Note: Averages were calculated using Isoplot v. 3.09a (Ludwig, 2004). Minimum age represents weighted average of the youngest cluster of concordant grains with overlapping ages. MSWD—mean square of weighted deviates. li—lower intercept

The minimum age of quartzite deposition has been more difficult to constrain. In many areas, the only firm minimum ages are provided by crosscutting 1.4 Ga granites. At Blue Ridge, for example, quartzites are intruded by multiple ca. 1436 Ma crosscutting pegmatite dikes (Fig. 2). These dikes cut the folded quartzite succession, requiring deposition of the sedimentary protoliths and two episodes of deformation and metamorphism (D_1/M_1 and D_2/M_2) prior to dike emplacement. One of the pegmatite dikes (sample J03-BR4) was observed to deflect foliation in host-rock quartzite and schist, suggesting that some degree of deformation, perhaps involving local fabric reactivation, might have accompanied magmatism at 1436 Ma. However, the dikes are otherwise strongly discordant with respect to the kilometer-scale syncline (F_2) that dominates exposures along Blue Ridge, and they are interpreted to postdate deformation and metamorphism. Similar crosscutting relationships are well documented across southern Colorado. In the Needle Mountains (Fig. 1), folded quartzite and schist of the Uncompahgre Formation are sharply truncated by the coarse-grained 1442 ± 3 Ma Eolus Granite (Gibson and Harris, 1992; Gonzales and Van Schmus, 2007). In the Sangre de Cristo Mountains (Fig. 1), quartzite is intruded by the 1434 ± 2 Ma Music Pass pluton (Jones and Connelly, 2006). These relationships not only require that quartzites were deposited prior to granitic magmatism, but they additionally require that the successions were multiply deformed and buried to granitic emplacement depths (~8 km for the Eolus Granite; Dean, 2004) prior to intrusion.

The best minimum age constraints for the timing of deposition come from apparent intrusive relationships, where ca. 1700 Ma granites are in contact with quartzite of the Ortega Formation in the Cimarron Mountains, northern New Mexico (Pedrick et al., 1998). Where the contact is observed, there are domains that contain quartz pods and inclusions within granite that are interpreted to be partly digested quartzite xenoliths. Based on these relationships, deposition of the Ortega Formation would be constrained at ca. 1700 Ma by the underlying rhyolite (1700 ± 25 Ma; Silver, 1984) and intrusive granite (1703 ± 10 Ma; Pedrick et al., 1998). This tight bracketing may be explained by granite-rhyolite associations where shallow-level plutons fed caldera-related rhyolites mainly before, but also overlapping in time with, quartzite deposition at 1700 Ma. This is our preferred interpretation as it is in agreement with data from the Mazatzal Group of Arizona where caldera-related rhyolites intrude quartzites (Brady, 1987) and 1701 ± 2 Ma rhyolites are interlayered with quartzite (Cox et al., 2002b).

Other minimum ages come from preliminary analyses of monazite grains in the Ortega Mountains of the northern Tusas Mountains, New Mexico (Kopera, 2003; Kopera et al., 2002). Here, detrital monazite cores with ages that range from 1853 to 1725 Ma have metamorphic overgrowths with ages of 1689 ± 8 Ma and 1670 ± 3 Ma that are interpreted to reflect early metamorphism during burial of quartzites by thrusting during the Mazatzal orogeny. These preliminary constraints place a minimum age for the Ortega Formation deposition at 1689–1670 Ma (Kopera, 2003).

Sedimentary Provenance

The bulk of the detrital zircon from all samples is Paleoproterozoic in age and defines a relatively narrow range of ages (1800–1700 Ma). Peak detrital ages vary somewhat but similarly display a narrow age range (1762–1700 Ma), and systematic shifts correspond to the age of the underlying basement. Detrital zircon morphologies are consistent with minimal transport and derivation from dominantly igneous source rocks. The range of detrital zircon ages closely corresponds with the general age range of juvenile basement assemblages of the Yavapai Province exposed across the region, and the peak detrital ages agree well with published U-Pb zircon ages of underlying basement assemblages locally (Figs. 5–7; Reed et al., 1993; Karlstrom et al., 2004). These results and observations suggest that the quartzite successions formed from first-cycle sediments characterized by a relatively juvenile population of detrital zircon derived almost exclusively from local source regions, presumably mainly from granitoids. The first-cycle character is also suggested by the general textural immaturity of the quartzites and the local abundance of volcanic phenocrystic quartz (Cox et al., 2002b). Minor amounts of Archean detrital zircon (up to 5%) are interpreted to reflect limited (and in many cases completely absent) sedimentary input from the Wyoming Province to the north (Fig. 1) but might also reflect reworked sedimentary rocks or unrecognized, Archean-aged crustal fragments that were possibly incorporated into the Paleoproterozoic accretionary orogen (Hill and Bickford, 2001). Mazatzal-aged (ca. 1650–1600 Ma) detritus was not recognized in any of the quartzites sampled, and the minimum detrital ages described previously closely coincide with the culmination of the Yavapai orogeny (1710–1700 Ma; Karlstrom and Bowring, 1988). Although the absence of Mazatzal-aged detrital zircon could simply represent depositional systems that derived material exclusively from northern, older (>1700 Ma) source terranes, our preferred interpretation is that quartzites were deposited ca. 1700–1680 Ma, prior to accretion of the Mazatzal Province to the south. Regional observations and constraints supporting this interpretation are discussed later.

In the Uncompahgre Formation of southwestern Colorado, the basal conglomerate and Q4 units are separated stratigraphically by more than 2 km (Harris and Eriksson, 1990), yet the detrital zircon age spectra are similar, and the peak ages do not vary significantly (Fig. 5; Table 1). Similar relationships are documented in basal conglomerate and quartzite exposed

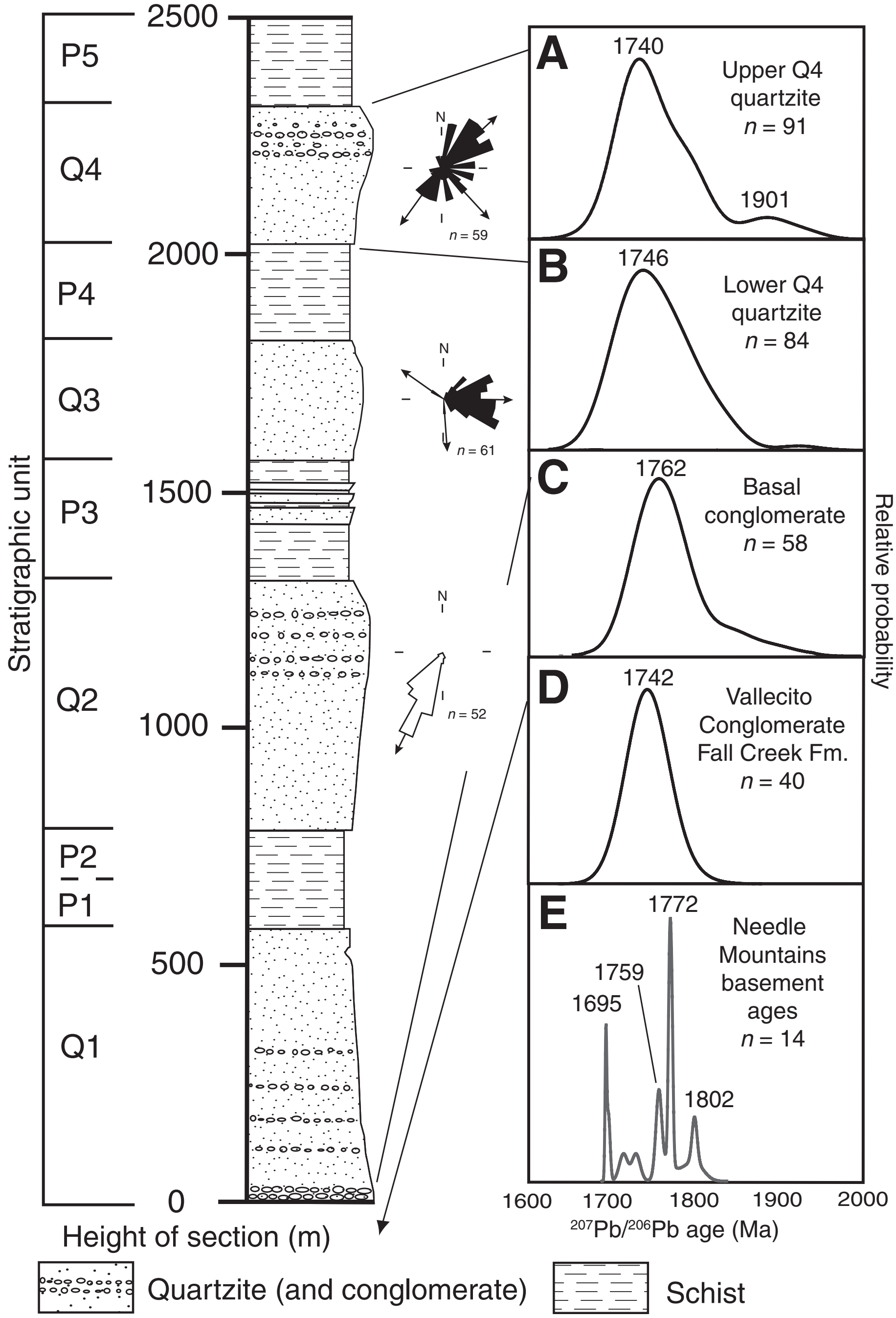

Figure 5. Lithostratigraphic section of quartzite and conglomerate (Q) and pelite (P) of the Uncompahgre Formation (after Harris and Eriksson, 1990). Paleocurrent data are summarized from Harris and Eriksson (1990) and are shown next to the corresponding stratigraphic interval. Open bars represent trough cross-beds, and filled bars represent tabular-planar to tangential cross strata. Detrital zircon $^{207}Pb/^{206}Pb$ ages (≤3% discordant, Proterozoic grains) and basement U-Pb crystallization ages for the Needle Mountains, Colorado, are also summarized. The Vallecito Conglomerate is interpreted to lie stratigraphically beneath the Uncompahgre Formation (Zinsser, 2006), but the thickness and detailed stratigraphy of this unit are not completely understood. Relative probability diagrams for: (A) Uncompahgre Formation upper Q4 quartzite; (B) Uncompahgre Formation lower Q4 quartzite; (C) Uncompahgre Formation basal conglomerate; (D) Fall Creek Formation of the Vallecito Conglomerate; and (E) basement U-Pb crystallization ages for exposures in the Needle Mountains (Gonzales and Van Schmus, 2007; Jones et al., 2005; Gonzales, 1997).

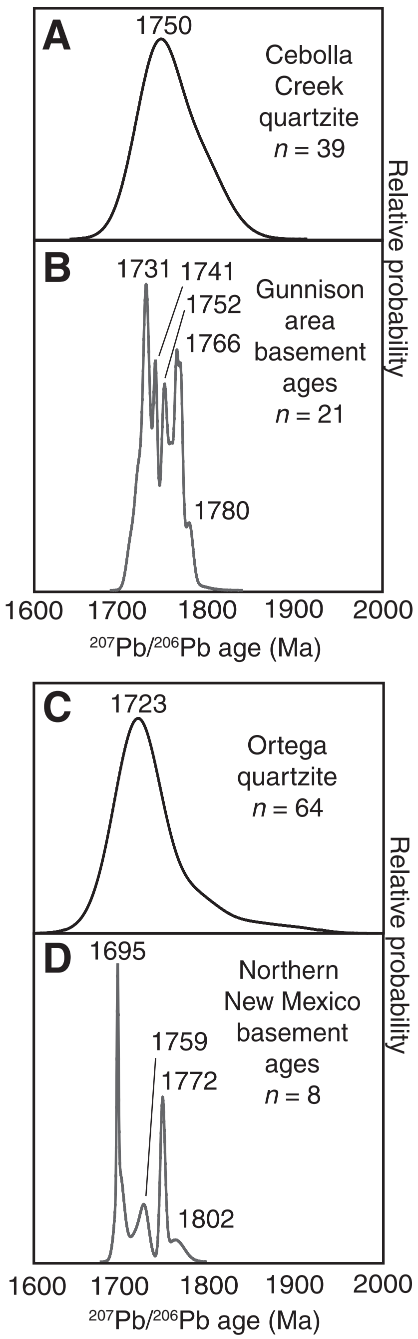

Figure 6. Summary of detrital zircon $^{207}Pb/^{206}Pb$ ages (≤3% discordant, Proterozoic grains) and basement U-Pb crystallization ages for the Gunnison area, Colorado, and northern New Mexico. Relative probability diagrams for: (A) quartzite exposed along Cebolla Creek, Colorado; (B) basement U-Pb crystallization ages in exposures in the Gunnison area, Colorado (Bickford et al., 1989b; Jessup et al., 2006); (C) Ortega quartzite exposed in the Tusas Mountains, New Mexico; and (D) basement U-Pb crystallization ages for exposures in northern New Mexico (Karlstrom et al., 2004, and references therein).

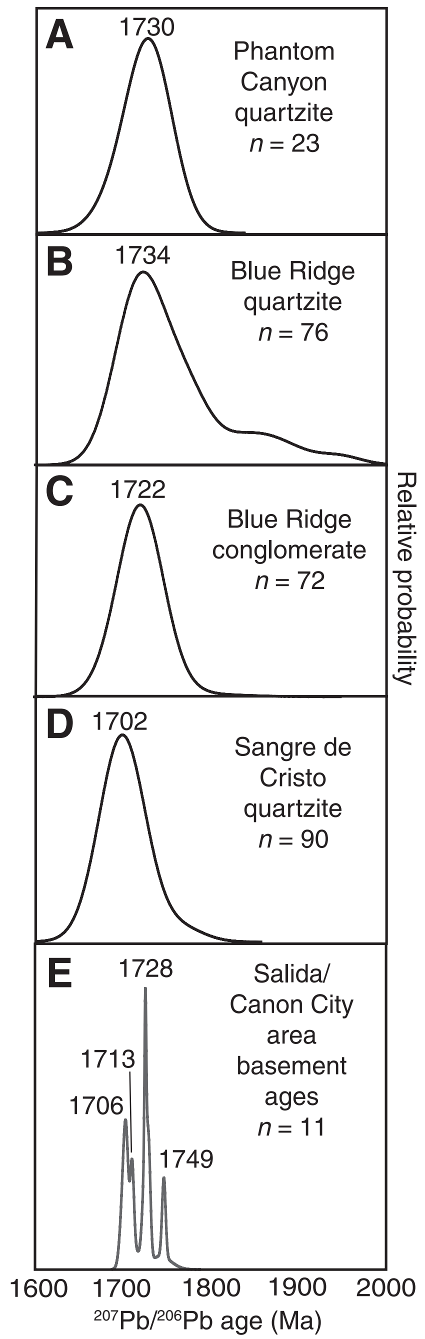

Figure 7. Summary of detrital zircon $^{207}Pb/^{206}Pb$ ages (≤3% discordant, Proterozoic grains) and basement U-Pb crystallization ages for the Salida and Cañon City area, Colorado. Relative probability diagrams for: (A) quartzite exposed along Phantom Canyon; (B) quartzite exposed at Blue Ridge; (C) basal conglomerate exposed at Blue Ridge; (D) quartzite exposed in the Sangre de Cristo Mountains; and (E) basement U-Pb crystallization ages for exposures in the Salida and Cañon City area, Colorado (Bickford et al., 1989a, 1989b; Jones and Connelly, 2006).

along Blue Ridge (Figs. 7B and 7C). The broadening of detrital zircon age spectra upward through the stratigraphic section suggests that the depositional systems evolved through time to reach older Proterozoic source terranes to the north. However, the relatively small shift in peak ages indicates that the depositional systems were still dominated by locally derived Paleoproterozoic-aged detritus throughout the depositional history of even the thickest (>2 km) metasedimentary successions.

Depositional Environment

Detrital zircon characteristics, quartzite textures, and crosscutting relationships of metasedimentary successions exposed throughout Colorado and northern New Mexico indicate that sediment was derived from local volcanic and/or plutonic sources. Quartzites in the southern Yavapai Province are underlain by voluminous rhyolite, whereas quartzites to the north are not directly associated with rhyolite but were deposited during prolonged granitic magmatism throughout the same region. In thicker, more complete successions where sedimentological data are available, there is a facies progression from alluvial to shallow marine in the lower units, and the middle and upper units are dominated by shallow-water marine deposits (Harris and Eriksson, 1990; Soegaard and Eriksson, 1985). Interlayering of fine-grained units and quartzite layers (Fig. 5) is interpreted to represent shoaling cycles attributed to eustatic oscillations and/or changing subsidence rates due to tectonism at the basin margins (Harris and Eriksson, 1990). Paleocurrent data and the nature of cross-bedding indicate a change from more linear transport of sediment in the lower parts of the successions to more distributed transport and/or reworking in the shallow-marine environment (Fig. 5; Harris and Eriksson, 1990). The spatial distribution of facies and paleocurrent patterns indicate that depositional basins were deeper to the south and that sediment was dominantly derived from the north (Figs. 2 and 5; Harris and Eriksson, 1990; Reuss, 1974). Similarities between detrital zircon age spectra and peak ages of some samples suggest that multiple successions were likely derived from the same source rocks and deposited within a single basin (Fig. 7). However, based on the facies distribution patterns, paleocurrent data, variable rhyolite/granite association, and outcrop extents of different successions, it is difficult to envision deposition occurring in a single regional basin. Instead, we envision multiple basins or subbasins that were oriented NE-SW, parallel to the southern Laurentian margin at the time of deposition (see Fig. 1 for approximate extents).

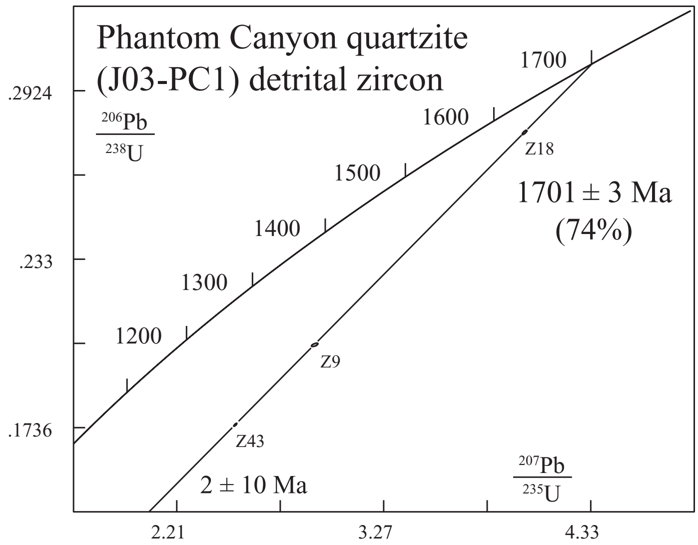

Figure 8. U-Pb concordia diagram for isotope dilution–thermal ionization mass spectrometry (ID-TIMS) analysis of youngest identified detrital zircon grains from quartzite exposed along Phantom Canyon, Colorado. The age was determined by linear regression through the three fractions, and probability of fit (%) is indicated in parentheses. Zircon fraction numbers refer to grain identification numbers reported in Jones (2005). For complete data set, see GSA Data Repository Table DR2 (see text footnote 1).

Cox et al. (2002b) argued for deposition of the Mazatzal Group in Arizona in an intra-arc basin based on (1) the compositional characteristics of the sediment; (2) the spatial and temporal association with felsic volcanic rocks; (3) the timing of sedimentation with respect to volcanism; and (4) a progressive change in upsection sediment provenance. An intra-arc setting helps to explain the predominantly felsic character of volcanism preceding sedimentation, and the temporal progression from volcanism to sedimentation is interpreted to represent the transition from an active arc to a relatively stable continental setting (Cox et al., 2002b). The relatively shallow nature of intra-arc basins helps to explain the prevalence of shallow-marine facies throughout the depositional history of the successions, where changes in water depth were controlled by eustatic effects and/or local subsidence rates. The Mazatzal Group is most similar to the Ortega Formation in New Mexico, especially in terms of the rhyolite association, and the two successions occur approximately along strike parallel to the Yavapai-Mazatzal Province boundary (Fig. 1). Thus, it seems reasonable that these two successions were deposited in similar basins within an active arc along the southern margin of the Yavapai Province ca. 1700 Ma. Quartzite successions to the north that lack underlying rhyolite were more likely deposited in basins developed along the continental margin away from the active arc. Quartzite successions exposed even farther to the north (i.e., Coal Creek and Park Range localities) might have been deposited in epicontinental basins, because these localities are hundreds of kilometers from the southern margin of the Yavapai Province, and there is not an apparent spatial association with coeval magmatism. However, the ages of these successions are not well established.

Regional Constraints on Quartzite Deposition

Zircon from Vadito Group rhyolite underlying quartzite of the Ortega Formation in the Tusas Mountains, New Mexico (Fig. 2), yielded U-Pb ages of ca. 1700 Ma (Bauer and Williams, 1989). Rhyolite layers locally grade into quartz-rich metasedimentary rocks, which include trough-bedded quartzites and, thus, are interpreted to represent part of a continuous stratigraphic succession. Detrital zircon characteristics of quartzite from the Ortega Formation are nearly identical to all of the quartzites exposed to the north in southern Colorado (Fig. 4), suggesting that all of the successions are broadly correlative. Outcrop characteristics, crosscutting relationships, and/or limited detrital zircon data from other quartzites exposed in central and northern Colorado (e.g., Coal Creek quartzite; Aleinikoff et al., 1993) suggest that additional correlative successions exist in the northern Yavapai Province (Fig. 1). However, additional work is needed to test these correlations.

Regional correlations are strengthened by the consistent structural style, orientation, and magnitude of crustal shortening exhibited by quartzite successions exposed throughout the southern Yavapai Province. Williams (1991) described deformation in the Tusas Mountains, northern New Mexico, that involved north-directed kilometer-scale folding and thrusting of the Ortega and Vadito Group quartzite-rhyolite succession and underlying basement assemblages. Quartzites of the Ortega Formation record a minimum of 50% shortening, which was accommodated primarily by reverse-slip ductile shearing, ductile thrusting, and imbrication (Williams, 1991). In the Needle Mountains, southern Colorado, folded quartzite and schist of the Uncompahgre Formation underwent early thin-skinned, north-directed thrust faulting followed by upright folding into a large (>10 km), complex cusp-shaped fold (Harris et al., 1987; Harris, 1990). Localized quartzite exposures across central and southern Colorado are commonly exposed in tight, upright synclinal "keels" that formed during regional subhorizontal, northwest-southeast crustal shortening (e.g., Gooseberry Gulch syncline; Reuss, 1974), and they are interpreted to represent the preserved roots of much larger folds.

The structural styles and deformation described here are all consistent with Mazatzal-aged deformation documented in exposures throughout the southwestern United States (Karlstrom and Bowring, 1993). Deformation associated with this orogenic episode primarily affected Arizona and New Mexico but also propagated northward into Colorado. The "Mazatzal deformation front" represents the approximate northern extent of these effects (Fig. 1; Karlstrom and Bowring, 1993; Karlstrom and Daniel, 1993), and all of the quartzites sampled for this study occur south of this deformation front. The metamorphic monazite ages described from Ortega Formation quartzite in the Tusas Mountains of northern New Mexico agree well with the age of progressive D_1 and D_2 deformation of the underlying Moppin Complex (ca. 1690–1630 Ma) and Vadito Group in the same range (Davis, 2002). Similarly, Read et al. (1999) argued that deformation (progressive development of S_1 and S_2) and metamorphism of the Ortega Formation in the Rincon Range, New Mexico, was broadly synchronous with emplacement of the 1682 ± 7 Ma Guadalupita pluton. Structures that formed during the Mazatzal orogeny in Arizona are characterized by foreland thrust belt geometries, and estimates of shortening related to northwest-directed thrusting between 1692 and 1630 Ma range from 35% to greater than 50% (>18 km; Puls, 1986; Doe and Karlstrom, 1991; Karlstrom and Bowring, 1993). These age estimates agree well with minimum age constraints described here and confirm that quartzite deposition in the southern Yavapai Province predated the Mazatzal orogeny.

Possible Laurentian Correlative Sequences

Paleoproterozoic metasedimentary successions containing abundant orthoquartzite occur elsewhere throughout southern Laurentia, most notably in the upper part of the Midwestern United States (Fig. 1). Baraboo interval quartzites occur in seven geographically separate but lithologically and stratigraphically similar successions (Fig. 1; Dott, 1983; Dott and Dalziel, 1972). The red, supermature quartz arenites are underlain by ca. 1750 Ma potassic rhyolite and epizonal granite (Smith, 1983; Van Schmus, 1978), and they were deposited at 1730–1650 Ma (Holm et al., 1998b) on polydeformed, Penokean-aged basement to the north (1870–1820 Ma; Van Schmus et al., 1993) and ca. 1800–1760 Ma crust to the south, which has recently been interpreted to represent the northeastern extension of the Yavapai Province (NICE Working Group, 2007). Deposition is thought to have occurred in a tectonically stable passive-margin setting (Dott, 1983), and sedimentary characteristics suggest two general depositional environments: an early braided fluvial system (Henry, 1975; Dott, 1983) and a later tidally influenced shelf environment (Davis, 2006). Recent recognition of feldspar-free paleosols and evidence for extreme chemical alteration of quartzites suggests that unusually intense chemical weathering accompanied deposition (Medaris et al., 2003).

The Baraboo Quartzite, which is exposed in a megascopic east-west–trending, doubly plunging syncline in southern Wisconsin, is characterized by detrital zircon with an age range of 1866–1712 Ma (Medaris et al., 2003), and similarities in detrital zircon ages among Baraboo interval quartzites are interpreted to confirm the long-standing correlation of the various successions (Medaris et al., 2003; Van Wyck and Norman, 2004; Holm et al., 1998b). Absolute minimum age constraints on quartzite deposition are restricted to localized crosscutting igneous bodies emplaced during Mesoproterozoic regional magmatism. However, a minimum depositional age of 1630 Ma is inferred based on a sharp break in basement cooling ages that corresponds well with the northern limit of quartzite deformation (Romano et al., 2000; Holm et al., 1998b). The close spatial coincidence of the deformation front in quartzites and the ca. 1630 Ma thermal front in underlying basement assemblages is interpreted to represent thin-skinned fold-and-thrust deformation accompanied by low-grade regional metamorphism during Mazatzal-related tectonism across the Lake Superior region (Dott, 1983; Holm et al., 1998b).

TECTONIC IMPLICATIONS

The deposition of thick (1–2 km), supermature quartzites during an ~20 m.y. interval between the Yavapai and Mazatzal orogenies in the southwestern United States has implications for the regional tectonic setting and, possibly, for the environmental conditions that accompanied sedimentation. The regional extent of likely correlative quartzite exposures requires that numerous depositional basins were developed across the southwestern United States at ca. 1700 Ma to accommodate the influx of locally derived sediment. Basins to the south likely formed in an intra-arc setting, and basins to the north likely formed along the continental margin and in the continental interior. Although deposition occurred during a tectonic "lull" between regional orogenic episodes, the observation that quartzite was deposited on 1710–1700 Ma granitoids in southern Colorado requires rapid exhumation of plutonic rocks in the 5–10 m.y. preceding deposition. Thickening patterns observed in the Mazatzal Group and restored fault geometries (Fig. 9; Doe and Karlstrom, 1991) show that depositional basins were bounded by growth faults that were active during the accumulation of ~1.5 km of strata (Cox et al., 2002b). Basin development and the onset of sedimentation in New Mexico and Arizona were accompanied by voluminous extrusion of high-silica rhyolite, and quartzite deposition in southern Colorado coincides with a prolonged episode of voluminous postorogenic granitic magmatism between 1700 and 1666 Ma (Anderson and Cullers, 1999). These relationships suggest that regional crustal extension occurred at this time, exhuming recently formed basement assemblages and accommodating voluminous magmatism at deeper crustal levels and widespread sedimentation at the surface.

The temporal overlap between quartzite deposition and regional magmatism suggests that these events record different yet contemporaneous processes that were widespread throughout the newly accreted Yavapai Province. Any tectonic model must account for the regional extent of quartzite exposures (Fig. 1), contemporaneous sedimentation and felsic magmatism due to crustal extension, and the transient nature of basin development and inversion during protracted accretionary orogenesis along the southern Laurentian margin. Giles et al. (2002) proposed a tectonic model for the cyclical evolution of Paleoproterozoic basins in Australia involving intermittently extending continental crust in the overriding plate of a long-lived subduction system. Extension and basin development up to 1500 km into the Australian plate interior occurred between 1.80 and 1.67 Ga during intervals of slab rollback, punctuated by transient shortening during episodes of renewed accretionary orogenesis along the active margin (Giles et al., 2002). We believe that a similar model can be applied to the Paleoproterozoic tectonic evolution of the Yavapai Province (Fig. 10). An episode of slab rollback following the culmination of the Yavapai orogeny at ca. 1.70 Ga would have facilitated extension throughout the newly accreted lithosphere, resulting in rapid exhumation of basement granitoids, basin development, and widespread magmatism (Fig. 10). The accretion of the Mazatzal Province to the south would have caused basin closure and inversion through fold-and-thrust-style deformation between ca. 1.68 and 1.65 Ga (Read et al., 1999; Bauer and Williams, 1994).

Age constraints and other similarities between quartzite successions in the southwestern United States and the Great Lakes region suggest that sedimentation might have been broadly contemporaneous along nearly 1500 km of the southern Laurentian margin during the Paleoproterozoic. Quartzite successions in both regions are underlain by rhyolite and have similar lithological and sedimentary characteristics, maximum depositional ages for some units converge at ca. 1700 Ma (this study; Medaris et al., 2003), and deformation and metamorphism of the successions in both regions is inferred to have occurred during the Mazatzal orogeny (see previous; Dott, 1983; Holm et al., 1998b). There is an apparent time lag of ~50 m.y. between collapse and stabilization of the Penokean orogen and deposition of Baraboo interval quartzites (Holm et al., 1998a), suggesting that the tectonic setting during sedimentation might have varied along the Laurentian margin at this time. However, more recent studies suggest that Baraboo interval quartzites might have been deposited on Yavapai-aged crust (NICE Working Group, 2007), allowing for a closer temporal association between orogenesis and sedimentation in both regions. Although a proposed correlation requires careful and continued study, we believe that the close correspondence of ages and striking similarities between quartzites exposed along the Paleoproterozoic Laurentian margin provide a promising basis for comparing and

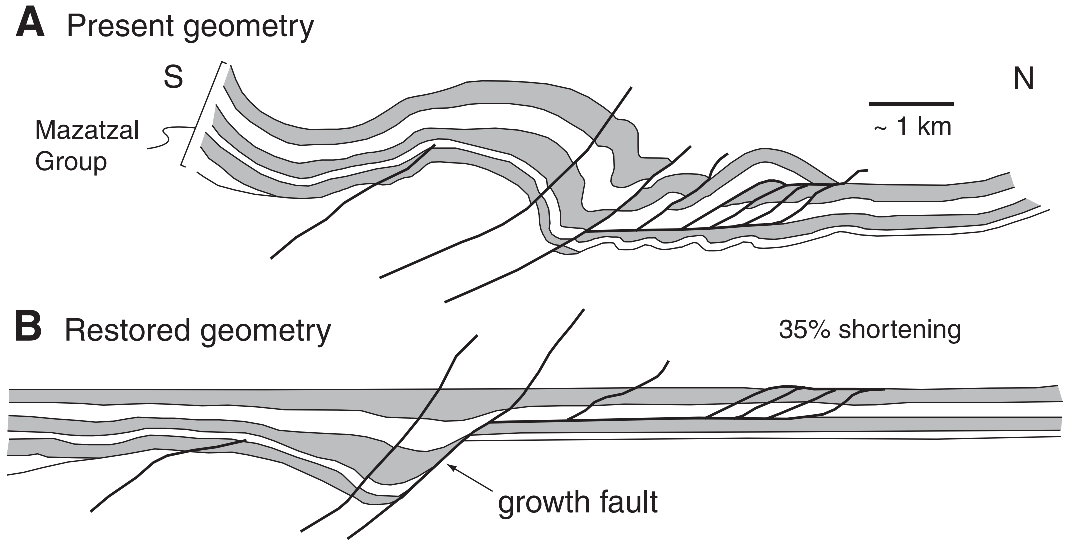

Figure 9. Cross sections of the Mazatzal thrust belt, Mazatzal Mountains, Arizona, showing the present (A) and restored (B) geometry of the Mazatzal Group. The Mazatzal Group consists of ~1.5 km of metarhyolite, quartzite, and schist that were deposited starting at 1701 ± 2 Ma (Cox et al., 2002b). The restored section indicates that the depositional basin was bounded by growth faults, which accommodated the influx of locally derived sediment. Basin inversion and development of the fold-and-thrust belt occurred during the Mazatzal orogeny and resulted in 35%–40% shortening (Doe and Karlstrom, 1991). This reinterpretation of the South Fork of Deadman Creek section (Doe and Karlstrom, 1991) used the original prerestored section and was updated by Doe through new mapping of digitized air photos, and it was restored using Midland Valley's 2DMove software.

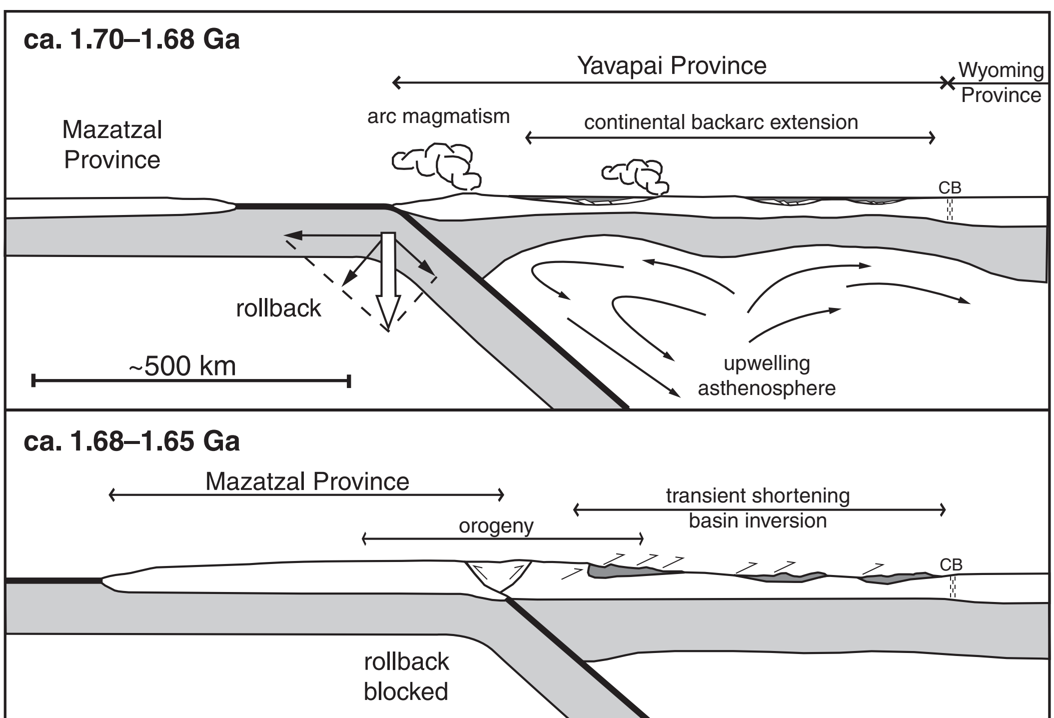

Figure 10. Tectonic model for quartzite deposition and deformation in the Yavapai Province, southwestern United States. Basin development, quartzite sedimentation, and widespread rhyolitic volcanism (and contemporaneous granitic magmatism) are interpreted to have occurred in the upper plate of a north-dipping subduction zone during an interval of slab rollback following the ca. 1.70 Ga culmination of the Yavapai orogeny. Basin closure and quartzite burial and deformation occurred during the Mazatzal orogeny. CB—Cheyenne Belt. Figure was modified from Figure 3 of Giles et al. (2002) (also after Magnani et al., 2004; Selverstone et al., 1999; Karlstrom et al., 2005).

possibly correlating Laurentian quartzites with other Proterozoic quartzite occurrences around the world.

THE QUARTZITE COMPOSITIONAL PARADOX

Paleoproterozoic quartzites exposed across the southwestern United States are interpreted to represent first-cycle sediments based on their juvenile detrital character and evidence described here for derivation from local, dominantly igneous sources throughout their entire depositional history. However, the extreme compositional purity and homogeneity of the quartzites is quite anomalous for first-cycle sediments deposited in a tectonically active environment. Cox et al. (2002b) argued for in situ mechanical and chemical alteration of labile framework grains as the primary mechanism for producing the mineralogical maturity of Mazatzal Group quartzites in Arizona. These postdepositional effects converted feldspar grains and lithic fragments to secondary pseudomatrix dominated by fine-grained phyllosilicate minerals. This interpretation is consistent with the textural characteristics of the quartzite and the geochemical characteristics of the quartzites and associated fine-grained rocks (Cox et al., 1995). Medaris et al. (2003) attributed the compositional maturity of Baraboo interval quartzites to extreme chemical weathering prior to deposition of the sediment. Their interpretation is supported by high chemical index of alteration values (96.8–98.6) for quartzite and the recognition of mature, feldspar-free paleosols underlying the successions. They suggested that microbial crusts or mats, perhaps analogous to modern-day cryptogamic soils, could have bound the sediment in the fluvial environment and contributed a biochemical component to the weathering process (Medaris et al., 2003).

It is widely recognized that a significant oxidation event occurred on Earth's surface around 2.0 Ga (Holland, 1984; Holland and Beukes, 1990) that was likely driven by an increased input of oxygen to the atmosphere due to increased sedimentary burial of organic matter between 2.3 and 2.0 Ga (Karhu and Holland, 1996). Progressive oxygenation of Earth's atmosphere is thought to have resulted in increased sulfide oxidation during continental weathering, which, in turn, caused a corresponding increase in marine sulfate concentration (Canfield et al., 2000). Shallow ocean waters were likely oxygenated during this time (Shen et al., 2003), but complete aeration of the oceans did not occur until a second major oxygenation event during the Neoproterozoic (0.80–0.54 Ga; Canfield and Teske, 1996). Instead, geochemical and isotopic data suggest that the deep ocean remained anoxic and became highly sulfidic due to increased rates of sulfate reduction (Shen et al., 2003; Canfield, 1998). The sulfidic transition is thought to have occurred at 1.84 Ga (Poulton et al., 2004), thus preceding Paleoproterozoic orogenesis and quartzite deposition in southern Laurentia. Pavlov et al. (2003) argued that methane fluxes resulting from sulfidic oceans and a low (but nonzero) oxygen atmosphere could have been 10–20 times the modern value, producing sustained Proterozoic atmospheric greenhouse conditions ca. 2.30–0.75 Ga. Chemical weathering would indeed have been extreme due to increasing oxygen levels, sulfide oxidation, and the resultant production of sulfuric acid. Weathering was further enhanced by prolonged greenhouse conditions that were unique to the transitional atmosphere and ocean chemistry of the Proterozoic. These various phenomena might explain the compositional maturity of Paleoproterozoic quartzite successions and also help to explain the lack of modern analogs in tectonically active environments.

More detailed petrologic and geochemical work is required to adequately evaluate the relative roles of diagenetic effects and/or extreme weathering in producing the compositional maturity that is observed in Paleoproterozoic quartzite successions throughout the southwestern United States. Modern examples of first-cycle quartz arenites occur in the Orinoco River basin within the Andean foreland of Venezuela and Colombia (Johnsson et al., 1988; 1991), where tropical weathering is extreme. However, there are no Phanerozoic analogs for thick, homogeneous successions of shallow-water, synorogenic quartz arenite in association with high-silica rhyolite. During the Paleoproterozoic, lithosphere was thick and stable enough to form large supercontinents but thin and hot enough that syntectonic basins were rapidly formed and deformed within wide accretionary orogens. Orthoquartzite successions represent a unique tectonic marker in the polyphase tectonic history of rocks in the southwestern United States, and they help us to better understand the nature, timing, extent, and symmetry of post–1.8 Ga events at the regional and global scale. Moreover, similarities among quartzites exposed throughout the region and along the Laurentian margin suggest that they also represent a widespread, and perhaps global, episode of sedimentation involving a distinctive syntectonic setting and unique climatic conditions, a combination that might make these units a signature lithology for Paleoproterozoic time.

CONCLUSIONS

Several important insights emerge from new geologic and geochronologic data from the southwestern United States. (1) New age constraints suggest that orthoquartzite successions were deposited ca. 1.70–1.68 Ga across Colorado, Arizona, and northern New Mexico. (2) Temporal overlap between regional sedimentation and ongoing ductile deformation and pluton emplacement in closely adjacent (tens of kilometers) blocks indicates that depositional basins were syntectonic (and syncontractional) in a broad sense. (3) Thick successions, evidence for rapid unroofing of basement granitoids, association with caldera rhyolites, and balanced cross sections suggest local extensional settings for quartzite-rhyolite assemblages. (4) A tectonic model involving intermittent slab rollback and widespread intraplate extension followed by rapid inversion of basins during continued accretionary orogenesis explains most aspects of the basins. (5) Detrital zircon data indicate local sources, relatively rapid deposition, and a first-cycle origin for the orthoquartzites. (6) Subtle shifts in the age of detrital zircon peaks that correspond to local basement crystallization ages reinforce the interpretation of a largely local origin (with limited far-traveled Archean detritus). (7) The ultramature composition of first-cycle orthoquartzite is attributed to some combination of postdepositional diagenetic effects and/or unusually intense weathering conditions, which were likely unique to the transitional atmosphere and ocean chemistry of the Paleoproterozoic.

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