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^{40}Ar/^{39}Ar AGE CONSTRAINTS ON THE DEPOSITION AND METAMORPHISM OF THE UNCOMPAHGRE GROUP, SOUTHWESTERN COLORADO

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Abstract—This paper presents new ^{40}Ar/^{39}Ar dates that constrain the age of deposition and of metamorphism of the Uncompahgre Group. This 2.5-km-thick quartzite and phyllite succession overlies granites as young as 1707 Ma and contains youngest detrital zircons of about 1709 Ma such that 1707-1709 Ma is its maximum age. A new ^{40}Ar/^{39}Ar date on muscovite from a (rare) granitic dike that crosscuts the Uncompahgre Group near Coal Bank Pass may approximate crystallization age and provides a minimum age for the Uncompahgre Group of 1704±5 Ma. Thus, the depositional age now appears constrained between 1707 and 1704 Ma. Samples within ~5 km of the 1435 Ga Electra Lake Gabbro give ^{40}Ar/^{39}Ar hornblende dates of ~1.46 Ga interpreted as either 1.46 Ga hornblende growth during Mesoproterozoic regional metamorphism or resetting of older hornblende in the aureole of the 1435 Ma pluton. Biotite dates of 1437±5 and 1438±5 Ma are interpreted to record metamorphism associated with emplacement of the 1435 Ma Electra Lake Gabbro. Samples in the northwestern Needle Mountains, at greater distance from the plutons, preserve evidence of older metamorphic events and indicate that the western and northwestern parts of the Needle Mountains were not heated above 350-500°C after ~1.6 Ga. An ^{40}Ar/^{39}Ar hornblende age of 1728±8 Ma in Irving Formation amphibolites is interpreted to represent a minimum age of hornblende growth; a 1607±6 Ma hornblende plateau may reflect additional alteration and resetting associated with younger (1.61 or 1.43 Ga) metamorphisms. Andalusite and sillimanite in the Uncompahgre Group define isograds of the contact aureole of the Eolus Granite and are interpreted to have grown ~1435 Ma. Andalusite in phyllites of the Uncompahgre Group overgrow two deformation fabrics and are deformed by a third, indicating polyphase deformation, with D1 and D2 pre-dating 1435 Ma pluton emplacement and D3 synchronous with pluton emplacement. The relative importance of 1.70-1.60 Ga versus 1.46-1.40 Ga deformation in forming D1 and D2 fabrics, as well as t-T history of the Uncompahgre Group from the surface to ~8 km depth by 1704 Ma and to 12-15 km depths by 1435 Ma remain unresolved. Fine grained muscovite gives ^{40}Ar/^{39}Ar ages as young as 1398±6 Ma suggesting slow cooling following emplacement of plutons.

AGE OF THE PRE-UNCOMPAHGRE GROUP BASEMENT

Geochronologic constraints bracketing the timing of deposition, deformation, and metamorphism of the Uncompahgre Group have been limited. Geologic relationships suggest that the Uncompahgre Group was deposited nonconformably on an older 1710-1780 Ma basement of volcanogenic Irving Formation (1786±10 and 1801±6 Ma; Gonzales and Van Schmus, 2007) and intrusive Twilight Gneiss). The age constraints for the Twilight Gniess are 1774±3 Ma (Jones et al., 2005) and 1754±7, 1757±7, 1759±6, 1766±15, 1771±3, and 1772±4 (Gonzales and Van Schmus, 2007); these ages reflect about 20 million years of arc-related plutonism. Synorogenic granites were emplaced in the Needle Mountains from 1707-1731 Ma (Gonzales and Van Schmus, 2007). One foliated dike that intrudes the Irving Formation yielded a U-Pb upper intercept age of 1731±10 Ma and the Tenmile Granite gave an upper intercept age of 1717±10 (Gonzales and Van Schmus, 2007). Keller et al. (2015) obtained zircon ages of 1707.4±2.4 and 1707.9±2.3 Ma for the syntectonic Whitehead Granite. Different igneous phases of the unfoliated Bakers Bridge Granite in the southwestern Needle Mountains gave upper intercept ages of 1695±2 and 1698±4 suggesting deformation was over or waning by 1695 Ma but there are no direct field relationships between this pluton and the Uncompahgre Group.

Timing of basement metamorphism is constrained by one fraction of sphene from the Twilight Gneiss that gave a nearly concordant weighted mean ^{207}Pb/^{206}Pb age of 1708.5±5.3 Ma and 5 fractions defined an upper-intercept age of ~1708 Ma (Gonzales and Van Schmus, 2007); this is interpreted to be the time of cooling for (pre-Uncompahgre Group) amphibolite-facies metamorphism. Jones et al. (2005) reported 1706±4 Ma zircon and sphene ages from a mafic dike interpreted to be the age of D2 amphibolite facies metamorphism in the basement, and a 1706±2 Ma zircon age on a granitic dike interpreted to cross cut D2 in the basement, but to have been deformed in a later D3 event. In summary, the basement had likely already undergone amphibolite to upper greenschist metamorphism and deformation (S1-S2) before syntectonic granites were emplaced from 1731 to 1708 Ma and may have undergone continued metamorphism and deformation that culminated ~1708 Ma.

Age Of The Uncompahgre Group

The Uncompahgre Group is a 2.5-km-thick succession of quartzite (quartz arenite protolith) interbedded with phyllite (metamorphosed shale). Rocks of the Uncompahgre Group are exposed in an arcuate belt that extends from the northwestern to the southeastern Needle Mountains (Fig. 1) and in two small outliers near Ouray and Rico about 30 km to the north and west of Figure 1 respectively. This succession is interpreted to

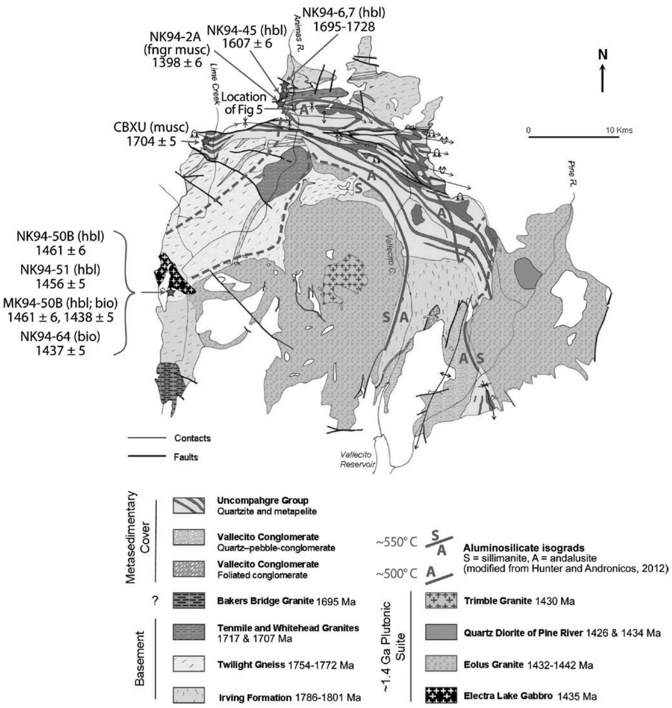


Figure 1. Proterozoic rocks of the Needle Mountains, modified from Zinnser (2006) based on Barker (1969), Tewksbury (1981), Harris et al. (1987), Gibson and Simpson (1988), and Gonzales (1988, 1997); ages summarized in text. For a color version, see Color Plate 9.

have been marine and fluvial sandstone, shale, and mudstone, underlain (Zinnser, 2006) by the Vallecito Conglomerate that consists of a thick succession of metamorphosed fluvial pebble- to cobble-conglomerate and quartz-rich sandstone with subordinate amounts of mudstone and siltstone. The combined Vallecito metaconglomerate and Uncompahgre quartzite-phyllite succession is referred to herein as the Uncompahgre Group (Zinnser, 2006).

Direct dates on interbedded volcanic rocks have not been obtained in the Uncompahgre Group. A possible metarhyolite bed in the unit was sampled in Pine Creek by Zinnser (2006), but no zircons were obtained from this sample (Jones, personal communication). The Uncompahgre Group is generally interpreted to have been deposited on unroofed 1717-1707 Ma plutons in the northern Needle Mountains (Barker, 1969; Harris et al., 1987; Gibson, 1990; Gonzales, 1997; Gonzales and Van Schmus, 2007) although contacts are variably sheared and the contact was interpreted as a thrust fault by Tewksbury (1985). Assuming a sheared depositional contact, a maximum age of 1707 Ma is inferred for the Uncompahgre Group.

Detrital zircons also provide a similar maximum depositional age. Aleinikoff et al. (1993) reported $^{207}Pb/^{206}Pb$ ages for detrital zircons from the Uncompahgre Group between 1655 and 1735 Ma. Four of the five fractions analyzed defined a co-linear trend with a "reference chord" that has an upper intercept age of ~1690 Ma which suggested that the Uncompahgre quartzite was deposited after 1690 Ma. Additional constraints on the maximum age of deposition were obtained by Jones et al. (2009) via detrital zircon analyses. Samples were collected from bottom to top of the Uncompahgre Group and results are shown in Figure 2. All of the quartzites are dominated by 1.80 to 1.70 Ga detritus with about 5-10% of older grains (3.2 to 2.2 Ga) that may represent far-traveled inputs from the Archean core of Laurentia. A distinct peak of 1,880 Ma is seen only in the upper Uncompahgre Group which may reflect transport from unexposed older crust in the region (Hill and Bickford, 2001). The mean peak age of the unimodal distribution of ages varies from 1740 to 1762, similar to the ages of underlying basement (E in Fig. 2). The youngest detrital grains in sample Q4 gave a weighted average of the youngest cluster of 10 concordant grains with overlapping ages of 1709±15 Ma (Jones et al., 2009). Based on the combined data, the maximum depositional age of the Uncompahgre Group is 1707-1709 Ma as

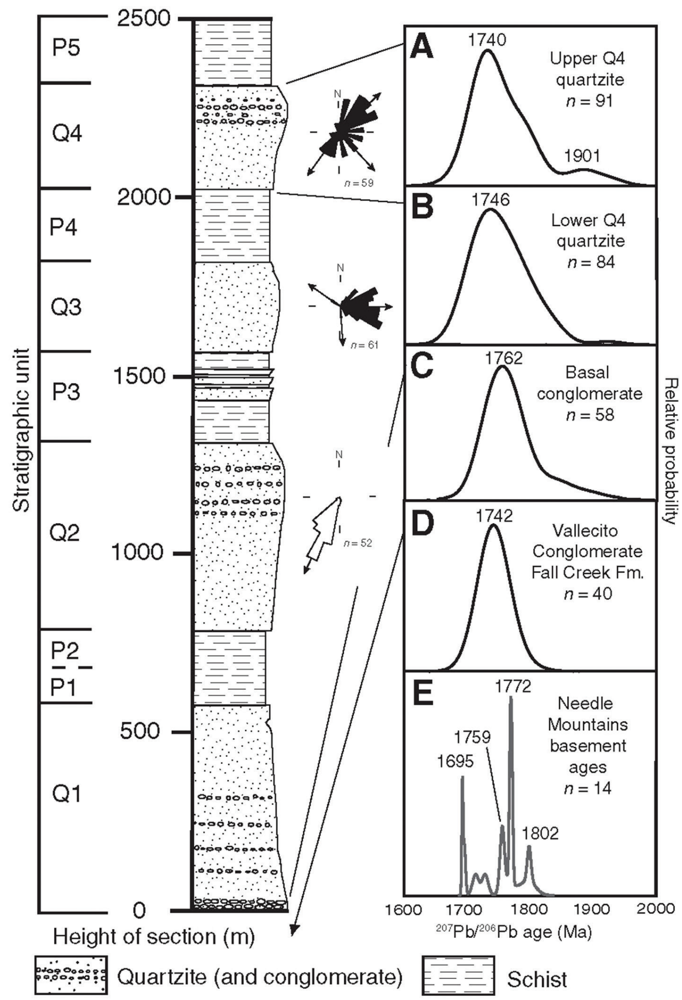


FIGURE 2. Lithostratigraphic section of quartzite and conglomerate (Q) and phyllite (P) of the Uncompahgre Group (from Fig. 5 of Jones et al., 2009). Paleocurrent data are summarized from Harris and Eriksson (1990) and are shown next to the corresponding stratigraphic interval. Open bars represent trough cross-beds, and filled bars represent tabular-planar to tangential cross strata. Detrital zircon $^{207}Pb/^{206}Pb$ ages (≤3% discordant) Proterozoic grains are in A-D and basement U-Pb crystallization ages in 2E (from Gonzales, 1997; Jones et al., 2005; and Gonzales and Van Schmus, 2007). The Vallecito Conglomerate is interpreted to lie stratigraphically beneath the Uncompahgre quartzite on the basis of field relationships (Zinsser, 2006).

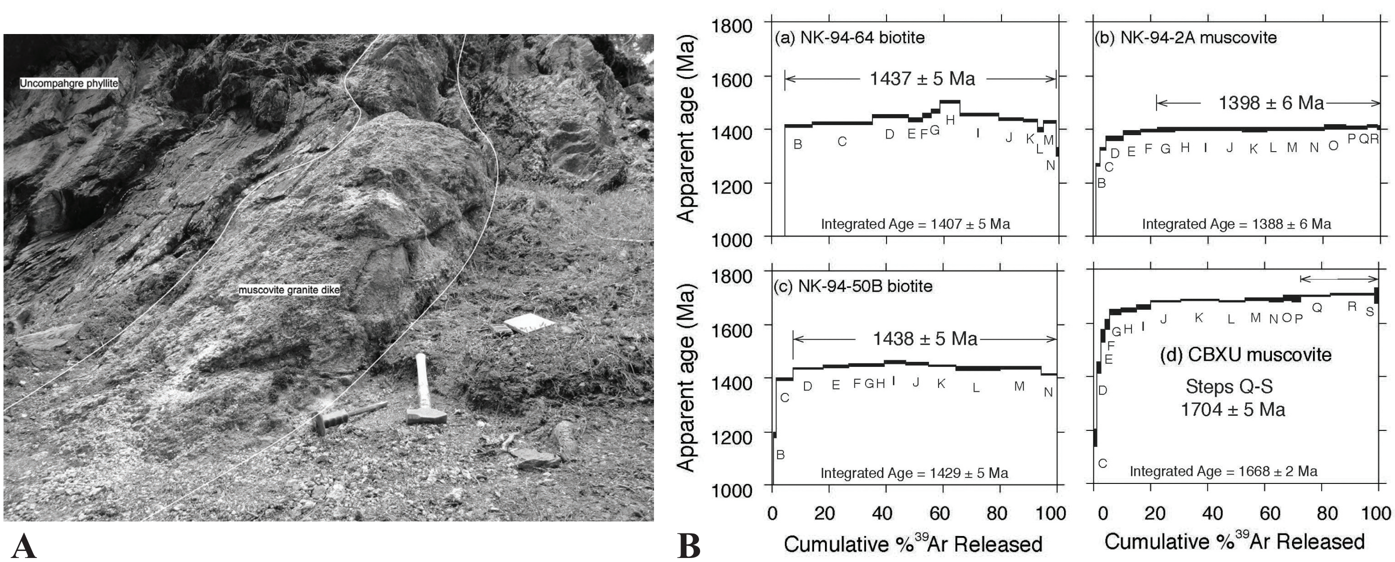
supported by both the youngest underlying pluton (1707 Ma) and the youngest detrital grains (1709 Ma). The potentially correlative basal Blue Ridge conglomerate about 200 km to the northeast in Colorado was deposited between 1.70 and 1.68 Ga (Jones et al., 2009).

A minimum depositional age for the Uncompahgre Group has been harder to constrain and many workers have simply reported deposition of the Uncompahgre Group to be bracketed between 1.7 and 1.4 Ga (Jones et al., 2009). However, Gonzales found several dikes of muscovite granite that intrude the Uncompahgre Group below the angular unconformity with Paleozoic strata in the Coal Bank Pass area. The dikes are coarse grained and undeformed to weakly foliated with minor boudinage developed in some outcrops (Fig. 3A). ^{40}Ar/^{39}Ar dating was conducted on muscovite from a dike as well as mica and amphiboles from elsewhere in the study area (Figs. 3B, 4). Age spectra were generated by step-heating in a double vacuum furnace or with a diode laser and all data are reported relative to Fish Canyon sanidine standard FC-2 with an assigned age of 28.201 Ma (Kuiper et al., 2008). The ^{40}K decay constant used is 5.463×10^{-10}/a from Min et al. (2000). Reported errors are at 2σ and reflect analytical precision only and not propagation of decay constant uncertainties. Additional analytical details are provided in the supplementary data provided on the NMGS website. Muscovite sample CBXu from one of the dikes at Coal Bank Pass area was analyzed using ^{40}Ar/^{39}Ar step-heating and yielded a spectrum with an overall climbing age pattern with the three highest temperature steps (Q, R, S) giving a terminal plateau age of 1704±5 Ma and a total gas age is 1668±2 Ma (D in Fig. 3B). The plateau age of 1704±5 is interpreted to be the time the dike cooled through 350-450°C following crystallization of the intrusive granite dike and hence is a minimum age for the Uncompahgre Group. The combined data suggest that the Uncompahgre Group was deposited between 1707 and 1704 Ma (discussed below); however, uncertainty about calibrating decay constants for the Ar-Ar and U-Pb systems (Renne et al., 2010, 2011) probably allows a potential 5-10 Ma geologic uncertainty in comparing results from these dating methods.

The Uncompahgre Group was intruded by a suite of ~1.43-1.44 Ga intrusive rocks (Cross et al., 1905; Barker, 1969; Burns et al., 1980; Ethridge et al., 1984; Harris et al., 1986; Harris, 1987; Gibson, 1987; Gonzales, 1988; Gibson, 1990; Harris, 1990; Gonzales, 1997; Gonzales and Van Schmus, 2007). The large Eolus Granite batholith has yielded U-Pb ages of 1435±3, 1438±9, and 1442±3 (Gonzales and Van Schmus, 2007) and 1431.7±0.5 (Keller et al., 2015). The Electra Lake Gabbro was dated as 1435±1. The Pine River pluton yielded concordant U-Pb ages ranging from 1425.9±0.9 Ma to 1433.7±1.0 Ma (Keller et al., 2015) and Trimble Granite, previously considered as ~1350 Ma (Bickford et al., 1968), has yielded a date of 1429.6±1.0 Ma (Keller et al., 2015) and 1457±17.8 Ma (Dembrowski and Gonzales, 2017). Many of these ages are based on regression of somewhat discordant zircon analyses and hence the geologic age uncertainty for the Eolus Granite and Electra Lake Gabbro emplacement may be somewhat greater than the reported analytical uncertainties. We interpret these plutons to have been emplaced in the interval 1.43-1.44 Ga.

DEFORMATIONAL HISTORY

Deformation timing of the Uncompahgre Group remains poorly constrained. Gibson and Harris (1992) recognized three deformational events that affected the Uncompahgre Group and called them $D_{cover\ 1\text{-}3}$. These post-dated at least two prior deformational events in the basement that they named $D_{basement\ 1\text{-}2}$. Both the complex map fold patterns (Fig. 1), and outcrop and thin section studies, show that the Uncompahgre Group un-



A B

FIGURE 3. **A.** Muscovite-bearing granite dike cutting phyllite of the Uncompahgre Group just west of Coal Bank Pass summit (dike location is 37.697198, -107.777443). The dike in this outcrop is not foliated and contains quartz, feldspar, and muscovite. For a color version, see Color Plate 10. **B.** ^{40}Ar/^{39}Ar age spectra from mica in the study area. The 1704±5 Ma ^{40}Ar/^{39}Ar date on muscovite from the dike shown in Figure 3A provides a minimum age for the Uncompahgre Group.

derwent multiple generations of D_c folding (Tewksbury, 1981, 1985; Harris et al., 1986, 1987; Harris, 1987, 1990; Zinnser, 2006). Zinnser (2006) interpreted early D1 north-directed thrusting (Harris et al., 1987). D2 macroscopic folding and south-directed thrusting (Tewksbury, 1985) produced the main folding event and the Uncompahgre synclinorium. S1 and S2 fabrics are truncated at the pluton margins and hence pre-date 1435 Ma pluton emplacment. D3 macroscopic folding and shearing associated with high-temperature low-pressure metamorphism (300-700°C at 3.5-4.5 kbars) was contemporaneous with 1435 Ma emplacement of the Eolus Granite. Zinnser (2006) reported partial basement-cover detachment but interpreted basement-cored thrust duplexes rather than cuspate-lobate basement-cover infolding (Harris et al., 1987).

As noted above, deposition of the Uncompahgre Group is now bracketed between 1704 and 1707 Ma, following rapid (several million years) exhumation of the middle crustal basement and syntectonic emplacement of the 1707 Ma Whitehead Granite (Gonzales, 1997; Gonzales and Van Schmus, 2007; Keller et al., 2015). Muscovite granites form at pressures higher than about 2.5 kbar where the water saturated solidus intersects the reaction ms + qtz = sill + Al_2SiO_5 + H_2O (Pattison et al., 1999). Thus, based on present geochronology, the Uncompahgre Group had to be deposited after 1707-1709 Ma, then be buried to ~8 km and intruded by granite by 1704 Ma. This suggests a possible continuum of deformation from 1707 to after 1704 Ma. In regional terms, this deformation might be considered late parts of the 1.75-1.70 Ga Yavapai orogeny, or might be considered part of the 1.70-1.60 Ga Mazatzal orogeny since it deforms the quartzite "cover" after unroofing of the Yavapai basement. The 1695 Ma Bakers Bridge granite is reported to be post-tectonic (Gonzales and Van Schmus, 2007) and may suggest that rocks were still at 5-10 km depths and that deformation had waned by 1695 Ma. In summary, timing of D1 (and perhaps) D2 in the Uncompahgre Group may have been between 1704 and 1695 Ma. But better constraints on timing of Uncompahgre Group D1 and D2 deformations are needed.

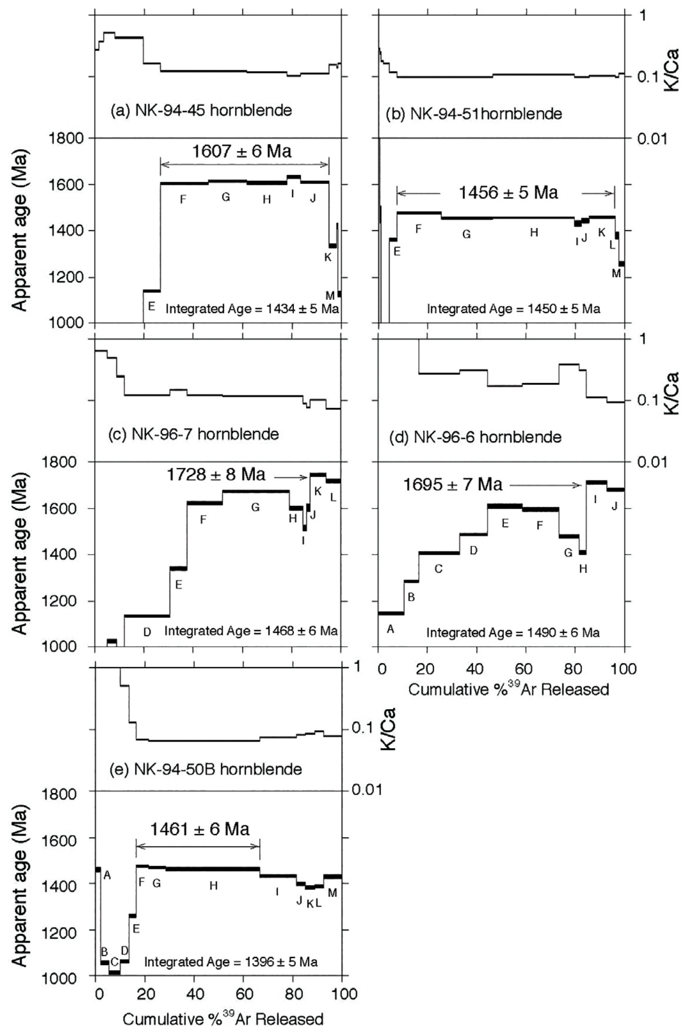


FIGURE 4. $^{40}Ar/^{39}Ar$ age and K/Ca spectra for hornblende separates collected from the ~1.78 Ga Irving Formation in the study area. The spectra are generally complex and show inverse correlation between age and K/Ca indicating that a young, high K, alteration phase is present within the dated amphiboles. Interpreted ages are generally based on choosing steps with the lowest K/Ca value that is assumed to indicate degassing of the amphibole that is least altered.

TIMING OF METAMORPHISM

New constraints on the metamorphic history of the pre-Uncompahgre basement comes from $^{40}Ar/^{39}Ar$ dating (hornblende and biotite) of metamorphosed volcanic rocks in the Irving Formation, and from Lu-Hf of garnet-bearing samples (Aronoff et al., 2014). Figure 4 shows $^{40}Ar/^{39}Ar$ age spectra for hornblende samples from two locations in the western Needle Mountains: from the southern contact aureole of the 1.435 Ga Electra Lake Gabbro, and in the northwestern outcrops about 10 km north of the nearest 1.43 Ga pluton margin. Hornblende samples near the pluton (NK94-50, 51) give plateau ages of 1456±6 and 1461±5 Ma. Biotite from NK94-50 and 64 give ages of 1438±5 and 1437±5 Ma. The apparent hornblende ages are 10-20 Ma older than the U-Pb age of 1435 Ma of the gabbro such that Mesoproterozic regional contact metamorphism may have begun before the plutons were emplaced, as is established by monazite and garnet dating in other areas of the Southwest (Aronoff et al., 2016). If so, the Coal Bank Pass area was not heated above 500°C at 1.46 Ga as shown by the preserved 1704 Ma muscovite age from CBXu. Alternatively, the 1.46 Ga amphiboles may have grown during pre-1700 Ma metamorphism in basement rocks and been partially reset during 1.43 Ga pluton emplacement. That is, if the hornblendes were formed and closed to argon diffusion at ~1.70 Ga, they could have undergone ~90% argon loss at 1.43 Ga to yield the 1.46 Ga apparent ages.

Areas at greater distance from the margins of the Eolus Granite and Electra Lake Gabbro preserve older hornblende ages within basement rocks of the Irving Formation just north of, and below, the basal Uncompahgre Group nonconformity. NK94-6 and 7 give very complex age spectra with oldest age segments of 1728±8 Ma and 1695±7 Ma. There is an inverse correlation between apparent age and K/Ca that suggests the hornblendes have been altered and contain a low closure temperature high-K phase that is mixing with the more pristine, lower-K hornblende. The assigned ages are taken from the portions of the spectra that yield the oldest ages and lowest K/Ca values (Fig. 4). Both hornblende samples, despite their apparent age difference could be at least 1728 Ma (and perhaps older), however, the younger 1695 Ma result has been more "contaminated" with the younger high-K phase. Thus the 1728 Ma age is interpreted to represent a minimum age for the timing of basement amphibolite facies metamorphism. A 1607±6 Ma plateau age from Irving Formation interleaved with the Whitehead Granite may reflect additional alteration and resetting associated with younger (1.70-1.60 Ga or 1.43 Ga) metamorphisms. Collectively, these preserved older ages show that the northwestern Needle Mountains are outside the amphibolite facies (>500°C) portion of the 1.435 Ga contact aureoles (Fig. 1). However, an ^{40}Ar/^{39}Ar age of 1398±6 Ma on fine grained muscovite from Uncompahgre Group phyllite suggests the region cooled through ~300-350°C at this time and that the ambient temperature surrounding the pluton may have been ~300°C at 1435 Ma. In summary of metamorphic conditions associated with the 1.43 Ga plutons, metamorphic assemblages suggest temperatures varied in the aureole from ambient conditions of ~300-400 to 700°C, at pressures between 3.5 and 4.5 kbars (Barker, 1969; Noel, 2002; Wu, 2007; Hunter and Andronicos, 2013). The presence of staurolite-andalusite-garnet rocks (Barker, 1969) require minimum pressures of ~3.5 kbar (Pattison et al., 1999) and the upper pressure constraint comes from the lack of kyanite, so the P-T path had to evolve below the aluminum silicate triple point and hence below 4.5 kbars.

The distribution and coexistence of aluminum silicate polymorphs have been used to investigate P-T conditions and timing of metamorphism of phyllites in Uncompahgre Group. Figure 1 shows an interpretation of aluminosilicate isograds adapted from Hunter and Andronicos (2013). Their study concentrated on the sillimanite-andalusite transition near the Pine River lobe of the Eolus Granite. Dashed lines extend this isograd more regionally parallel to the intrusive contact. They inferred that sillimanite grew via several reactions that were catalyzed by dissolution-precipitation (pressure solution) along shear zones that accompanied pluton emplacement. Hunter and Andronicos (2013) estimated peak metamorphic temperatures of 550–570°C and 4.1–4.5 kbars at this locality based on isochemical phase diagram calculations made using Theriakdomino software, using whole rock bulk compositions and the thermodynamic database of Holland and Powell (1998). Sillimanite + K-feldspar ± cordierite, without andalusite, is common within a few hundred meters of the contact suggesting metamorphic temperatures in excess of 650°C.

A wide zone containing andalusite extends about 10 km from the Eolus Granite contacts. This andalusite zone is bounded to the northeast by reaction isograds muscovite + chlorite = andalusite + biotite + H_2O, and where paragonite – muscovite (solid solution) + quartz = andalusite + plagioclase + muscovite (K-rich) + H_2O. For iron rich chlorite (Fe-mole% chlorite 1-0.5) this reaction occurs at temperatures between 500 and 550°C and pressures between 1 and 4 kbars (Pattison et al., 2002), with Mg-content increasing with higher P and T.

Figure 5 is from an area of andalusite phyllite along the Colorado Trail near the Animas River that will be visited on Day Zero of this field conference. Euhedral andalusite porphyroblasts, presumed to be ~1435 Ma contact metamorphic minerals overgrew the regionally dominant S1/S2 slatey cleavage in the phyllites and are rotated sinistrally relative to the dominant fabric (Fig. 5A) and cut by sinistral (top-south in the field) D3 shear zones (Fig. 5B, Zinnser, 2006).

CONCLUSIONS

1. Basement rocks of the Irving Formation (1786 to 1801 Ma) were intruded by the Twilight orthogneiss (granodiorite and tonalite) from 1754 to 1774 Ma, then by syntectonic granites from 1707 to 1731 Ma, then underwent protracted metamorphism to amphibolite grade from before 1728 Ma that culminated ~1708 Ma, and were intruded by late- to post-tectonic granites 1695 to 1698 Ma.

2. Middle crustal rocks were unroofed to the surface in a few-million-year interval between 1704 and 1707 Ma, then the Uncompahgre Group was buried by thrusts during D1 (and perhaps D2) deformation to depths of about 8 km before 1704 Ma muscovite-bearing granite intruded it.

3. 1430-1440 Ma granite and gabbro plutons were emplaced at 12-15 km depth during the regional Mesoproterozoic tectonism. D3 deformation took place during amphibolite facies contact metamorphism at 3.5-4.5 kbars (12-15 km depths) with aureole temperatures reaching 300-700°C.

RESEARCH QUESTIONS

1) Correlation and tectonic setting of quartzite successions: Available age constraints from quartzites in Colorado, New Mexico, and Arizona suggest several distinct ages of quartzite deposition in the Southwest. The oldest quartzites are 1704-1680 Ma and include the Uncompahgre Group (this paper), Blue Ridge Quartzite (Jones et al., 2009), and perhaps Ortega Quartzite (Kopera, 2003). A younger ~1650 Ma basin is recorded by the 1662-1600 Ma Manzano Group in central NM (Karlstrom et al., 2016), and Mazatzal Group and White Ledges Quartzite (Doe et al., 2013) in AZ. A Mesoproteroozic basin sequences is the 1500-1450 Ma Trampas Group of NM (Daniel et al., 2013) and Yankee Joe Formation of AZ and NM (Doe et al., 2012). It is unclear the extent to which each basin involved regionally blanketing sedimentary deposits versus structurally controlled syntectonic basins of more limited aerial extent.

2) How many orogenies (mountain building and beveling episodes) were there? — the need for better P-T-t-D paths: The Proterozoic orogenic belts have been interpreted in terms of evolution of a long-lived (1.8-1.0 Ga) convergent margin in Southwestern Laurentia (Karlstrom et al., 2001), but there has been debate about how best to define punctuated metamorphic and deformational episodes in local areas within this time period. The basal unconformities below each of the above quartzite successions can be used to track multiple orogenic episodes.

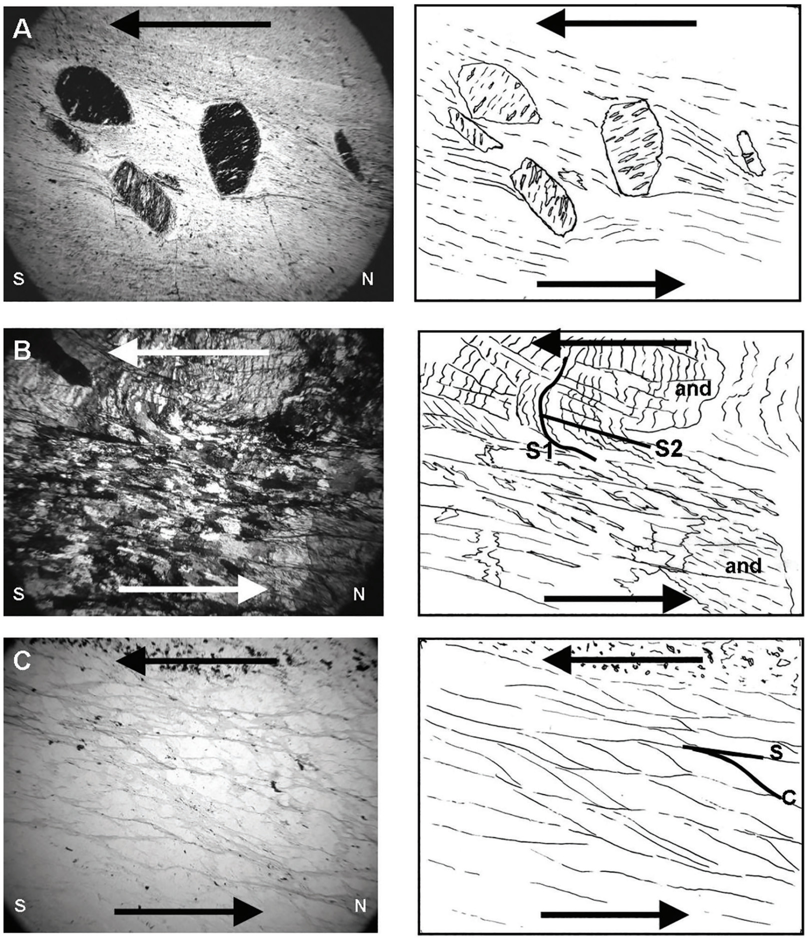


FIGURE 5. Shear fabrics from phyllitic rocks of the Uncompahgre Group near the northern basement-cover contact indicating top-to-the south shear. This shear sense is opposite of that previously reported and is incompatible with the cuspate basement-cover deformation model proposed by Harris et al. (1987). **A.** Sample KEP-7 is from phyllite P2, 1 km south of northern basement-cover contact in canyon of the Animas River showing oxide-rich andalusite pophyroblasts that overgrew S1/S2 and are variably sinistrally rotated within the D3 matrix fabric. **B.** Sample KN02-11 collected from same location as A showing andalusite grains that overgrow S2 crenulation cleavage and are sheared along S3. **C.** S-C fabric in quartz-chlorite shear zone from a thin phyllitic unit 500 m north of Elk Creek pack trail, 1 km east of Animas River indicating top-to-the south shear. For a color version, see Color Plate 11.

In the Needle Mountains, burial of Irving Formation volcanic rocks to amphibolite facies conditions, intrusion of arc plutons from 1754 to 1774 Ma, then syntectonic granites and peak metamorphism 1707-1731 Ma, with late- to post-tectonic granites as young as 1695 Ma. The implication of the new muscovite date is that unroofing of basement took place quickly as Uncompahgre Group rocks were deposited on a nonconformity between 1707 and 1704 Ma and then these sedimentary rocks were tectonically buried to depths of ~8 km by 1704 Ma with this deformation waning by 1696 Ma. Such rapid unroofing is possible in orogenic settings, as is rapid thrust burial of synorogenic sediments, such that this episode of burial to 8-km depths can be viewed as a continuation of the 1.75-1.70 Ga Yavapai orogeny, or as the next (Mazatzal) orogenic cycle where previously deformed Yavapai basement was unroofed before Uncompahgre Group deposition. The possibility of a 1.70-1.60 Ga “Mazatzal orogeny” (e.g., Karlstrom et al., 2004, 2016) is that D1 N-directed thrust burial (and perhaps some of the D2 shortening) took place 1.70-1.60 Ga and involved greenschist facies metamorphism and thrust fabrics that were strongly overprinted by 1.43 Ga higher grade metamorphic events. Evidence for a regional Mazatzal orogeny has been presented for areas to the north (Duebendorfer et al., 2015), along orogenic strike in the Wet Mountains (Aronoff et al., 2014), and in the Manzano Mountains to the south where 1.65-1.60 Ga deformation is recorded in pluton aureoles and by monazite dating (Karlstrom et al., 2016). But the importance of 1.70-1.60 tectonism remains poorly known in the Needle Mountains and in northern New Mexico.

3) Mesoproterozoic tectonism — the Picuris Orogeny and comparison between regions: In the Needle Mountains, the culminating orogenic event was the Picuris orogeny when Uncompahgre Group metasediments were at depths of 12-15 km by 1435 Ma as shown by 3.5 to 4.5 kbars pressure estimates from the Eolus Granite contact aureole. It may have lasted from before 1.46 Ga (hornblende ages) to 1.40 Ga (cooling ages of fine grained muscovite) and involved emplacement of voluminous 1.44-1.43 Ga plutons that facilitated pluton-enhanced deformation and metamorphism (Gonzales et al., 1996; Hunter and Andronicos, 2013). Detailed studies in different parts of the Proterozoic orogens of the Southwest are showing different histories that need to be understood and reconciled into a regional tectonic framework. In northern New Mexico, much or all of the penetrative fabric and triple point metamorphism (Aronoff et al., 2016) took place 1.45-1.40 Ga (Williams et al., 1999) during the Picuris orogeny (Daniel et al. 2013). In this area, the 1.50-1.45 Ga Trampas Group provides an example of rapid thrust burial of sediments to 12-15 km depths that took place about 1.45 Ga. In southern Colorado, Picuris orogeny involved lower crustal flow accompanying pluton emplacement (Jones et al., 2010). In central New Mexico, the Picuris orogeny is most strongly recorded in pluton aureoles (Kirby et al., 1995) and by Ar-Ar cooling ages (Shaw et al., 2005). The Picuris orogeny appears to have been an intracratonic event involving thermal softening related to widespread magmatism and lower crustal flow that allowed variable strain and metamorphic imprints from far- field stresses of a distant plate margin located in the region of modern-day Texas (Jones et al., 2015; Karlstrom et al., 2016).

4) The need for more precise geochronology: Tectonic events may have occurred at rates barely resolvable by currently available geochronology. Future U-Pb dates can be improved using chemical abrasion techniques (Mattinson, 2005) to decrease discordance of analyses. Decay constant errors between the U-Pb and Ar-Ar systems that allow 5-10 Ma of geologic uncertainty (Renne et al., 2010, 2011) need to be rec-

onciled. U-Pb chemical dating of monazite and xenotime within the Uncompahgre Group may be a promising direction for directly dating D1 and D2 episodes.

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Supplemental data can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2017001