# The nature and extent of the Mesoproterozoic Picuris orogeny in Colorado

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## ABSTRACT

The Mesoproterozoic is a controversial time within the Earth's history, and is characterized by high T/P ratios in metamorphic rocks, a large volume of extensional plutons, very few economic mineral deposits, and (arguably) a slow-down in plate tectonic processes. In Laurentia, ~1.48–1.35 Ga is well known as a time of ferroan magmatism. Recently, a ~1.50–1.35 Ga orogenic belt was proposed that spanned Laurentia from present-day eastern Canada to the southwestern United States. Unlike the preceding Paleoproterozoic Yavapai/Mazatzal orogenies and the subsequent late Mesoproterozoic Grenville orogeny, the early-mid-Mesoproterozoic Picuris orogeny in the southwestern U.S. was relatively unrecognized until about two decades ago, when geochronology data became more abundant. In multiple study areas of Arizona and New Mexico, deposition, metamorphism and deformation previously ascribed to the Yavapai/Mazatzal orogenies proved to be part of the ~1.4 Ga Picuris orogeny. In Colorado, the nature and extent of the Picuris orogeny is poorly understood. On this trip, we discuss new

evidence for the Picuris orogeny in the central Colorado Front Range, from Black Hawk in the central Colorado Front Range to the Wet Mountains, Colorado. We will discuss how the Picuris orogeny reactivated or overprinted earlier structures, and perhaps controlled the location of structures associated with Cambrian rifting, the Cretaceous-Paleogene Laramide orogeny, and the Rio Grande Rift, and associated mineralization. We will also discuss what made the Picuris orogeny, and the Mesoproterozoic unique within the Earth's history.

## INTRODUCTION

Globally, the Mesoproterozoic is characterized by a number of anomalies compared with pre- and post-Mesoproterozoic periods. These include a decrease in the number of passive margins, detrital zircons, greenstone-belt collisions, eclogites, granulites, carbonatites, and orogenic gold (Bradley et al., 2011), higher T/P ratios of metamorphic rocks, and more juvenile and thinned crust (Brown et al., 2020; Spencer et al., 2021). The reason for these anomalies is not known, but was interpreted previously as a slow-down of tectonic processes during the Columbia/Nuna-Rodinia supercontinent transition, or as a period of plate tectonics characterized by hot, thin, and low orogens (Spencer et al., 2021, and references therein). The Mesoproterozoic Picuris orogen of the southwestern U.S. (Daniel et al., 2013, 2022a,b), provides an opportunity to investigate and discuss these processes. The focus of this field trip is to examine the nature and extent of the Picuris orogen in the Colorado Front Range. We will also discuss how it reactivates earlier Paleoproterozoic structures and may control later Phanerozoic structures.

Proterozoic rocks of the southwestern U.S. (Figs. 1, 2) preserve a record of significant Paleoproterozoic crustal growth southward from the Archean Wyoming Province (present day coordinates), and experienced multiple orogenic events including the Paleoproterozoic Yavapai and Mazatzal orogenies (Whitmeyer and Karlstrom, 2007; Jones et al., 2009; Holland et al., 2020), and the Mesoproterozoic Picuris orogeny (Daniel et al., 2013). Voluminous ~1.48–1.35 Ga granitic magmatic rocks are also associated with the Mesoproterozoic, and make up about 25–30% of the exposed Proterozoic rock in the southwestern U.S. The occurrence of significant ferroan, granitic magmatic rocks, typically attributed to an extensional environment (Anderson and Morrison, 2005; Frost and Frost, 2022), and crustal thickening associated with the contractional Picuris orogeny overlap in time and space and present and an intriguing contradiction with respect to the tectonic setting of Laurentia during the Mesoproterozoic (Daniel et al., 2022a,b; Frost and Frost, 2022).

In Colorado, ~1.4 Ga deformation and metamorphism were previously recognized and interpreted as relatively localized events related to pluton emplacement or as reactivation along Paleoproterozoic foliations and shear zones (Fig. 2; Pedrick et al., 1998; Selverstone et al., 2000; Shaw et al., 2001; McCoy et al., 2005, Shaw and Allen, 2007; Allen and Shaw, 2011; Lytle, 2016). This field trip includes visits to exposures in the central Colorado Front Range and in the Wet Mountains (Fig. 2) to examine new evidence for ~1.4 Ga metamorphism and deformation, and discuss how to separate the Mesoproterozoic from older Paleoproterozoic events. We will discuss the larger scale nature of deformation across the southern margin of Laurentia, and how the Picuris Orogen correlates with the Baraboo and Pinware orogens of the midcontinent and eastern Canada, respectively (Fig. 1). We also highlight overprinting Cambrian rift structures and mineralized rocks, and Cretaceous–Paleogene structures and mineralized rocks associated with the Laramide orogeny. We will discuss how and why the Mesoproterozoic Picuris orogeny was different from earlier and later orogenies on Earth and how Proterozoic tectonism may have controlled later structures and mineralization.

GSA designated this as a Warren Hamilton field trip, which supports student participation. Warren B. Hamilton (1925–2018) integrated geology and geophysics into large-scale tectonic and planetary-scale syntheses. He was an outside-the-box thinker and always encouraged stimulating and thought-provoking discussion. In that spirit, this field trip will have ‘questions for discussion’ at each stop, where we encourage all to discuss those questions and others that may arise, and particularly include our early-career participants.

## PROTEROZOIC OROGENIC EVENTS IN COLORADO

### The Yavapai and Mazatzal Orogenies

The Paleoproterozoic Yavapai and Mazatzal orogenies were first defined in Arizona (Karlstrom and Bowring, 1988; Bowring and Karlstrom, 1990) and have subsequently been extended to the NE and across the midcontinent (Whitmeyer and Karlstrom, 2007). Paleoproterozoic amphibolite facies metasedimentary and metaigneous rocks in the Colorado Front Range (e.g., Gable, 2000; Widmann et al., 2000; Kellogg et al., 2008) were interpreted as juvenile arc terranes with associated basins that amalgamated and accreted to the Wyoming Craton part of Laurentia between ~1.8 Ga and ~1.6 Ga (Whitmeyer and Karlstrom, 2007). Alternatively, Jones et al. (2009) and Holland et al. (2020) proposed that the Paleoproterozoic rocks of the southwestern U.S. formed largely within a continental arc setting that experienced alternating periods of slab roll and extension to create back-arc basins that were subsequently closed and inverted by advancement of the subduction zone and compression. In general, two periods of orogenesis including the ~1.72–1.68 Ga Yavapai and ~1.65–1.6 Ga Mazatzal orogenies have been recognized across the southwestern U.S. for more than 35 years, which may or may not have been a continuous period of deformation (Jones and Connelly, 2006; Mahan et al., 2013). The resultant Yavapai crustal province is now a NE-trending zone of predominantly juvenile crust that extends from Arizona to Michigan (Fig. 2; Whitmeyer and Karlstrom, 2007), and forms most of the Proterozoic basement of Colorado. Calc-alkaline plutons intruded the Yavapai basement of Colorado between about ~1.66 Ga and 1.65 Ga. The Mazatzal crustal province extends from Arizona to Quebec and Labrador in Canada (Figs. 1, 2; Whitmeyer and Karlstrom, 2007), and probably includes older Paleoproterozoic crustal material (Holland et al., 2020) Between ~1.60 Ga and ~1.5 Ga Laurentia underwent a period of tectonic quiescence (Whitmeyer and Karlstrom, 2007; Doe et al., 2012; Aronoff, et al., 2016). Interestingly, deformation in the Mazatzal Mountains of Arizona is now known to be ~1.47–1.43 Ga (Doe et al., 2012; Doe and Daniel 2019), the general age of the Picuris orogeny.

**The Picuris Orogeny**

Mesoproterozoic ~1.5–1.45 Ga deposition of siliciclastic sediments in the southwestern U.S. was first reported in the Picuris Mountains, New Mexico (Jones et al., 2011; Fig. 1) and the upper Salt River Canyon, Arizona (Doe et al., 2012; Fig. 1). Additional rocks of this age are known from the Defiance uplift, Four Peaks, and the northern Mazatzal Mountains of Arizona (Doe et al., 2013, Mako et al., 2015; Doe and Daniel, 2019; Figs. 1, 2). These rocks and the underlying Yavapai and Mazatzal basement across much of central and northern New Mexico experienced greenschist to uppermost amphibolite facies metamorphism and deformation between ~1.44 Ga and ~1.37 Ga, including the Tusas and Taos mountains of New Mexico (Pedrick et al., 1998; Kopera, 2003; Fig. 2). Several areas also experienced emplacement of ~1.45–1.40 Ga granitic plutons and preserve contact metamorphic aureoles (Four Peaks, upper Salt River Canyon, southern Picuris Mountains; Fig. 2). The recognition of ~1.50–1.35 Ga deposition, regional metamorphism and deformation, and magmatism led to the proposed Picuris orogeny (Daniel et al., 2013; Aronoff et al., 2016; Bollen et al., 2022).

Mesoproterozoic, ~1.43–1.36 Ga metamorphism and deformation is also observed in the Wet Mountains, the Needle Mountains, and the region around the Black Canyon of the Gunnison, southern Colorado, Big Thompson Canyon of central Colorado, (Fig. 2; Shaw et al., 2001; McCoy et al., 2005; Jessup et al., 2006; Jones et al., 2010; Shah and Bell, 2012; Mahan et al., 2013; Lytle, 2016). Recent and ongoing research from the central Front Range of Colorado also indicates Mesoproterozoic deformation, not only reactivation along shear zones, but also pervasive folding (Lytle, 2016; Mahatma, 2019; Powell, 2020; Shockley, 2021). This is further discussed below.

The Picuris orogen is part of a larger, trans-Laurentian orogen that include the Baraboo and Pinware orogens of the midcontinent and eastern Canada, respectively (Daniel et al., 2022a, b; Fig. 1), This Pinware-Baraboo-Picuris orogenic belt is attributed to a convergent or accretionary plate margin across the southern margin of Laurentia (present-day coordinates). In eastern Canada, the ~1.51–1.46 Ga Pinware orogeny involved convergence and subduction within the proto-Grenville province in Labrador and eastern Quebec (Tucker and Gower, 1994; Gower and Krogh, 2002; Groulier et al., 2020). Similarly, the midcontinent Baraboo orogeny yielded 1493–1465 Ma muscovite $^{40}Ar/^{39}Ar$ ages, and plutons in that same age range (Medaris et al., 2021). The ~1.48–1.35 Ga Picuris orogeny in northern New Mexico involved convergence and possible collision between Laurentia and juvenile crust along the southern margin of Laurentia (Aronoff et. al., 2016). This created shortening and thickening of Paleo- and Mesoproterozoic rocks (Daniel and Pyle, 2006; Daniel et al., 2013; Aronoff et al., 2016; Daniel et al. 2022b).

Between ~1.48 Ga and 1.36 Ga, granitoids were emplaced in a broad belt spanning from the southwestern U.S. through the Baltic shield (Fig. 2; Windley, 1993; Karlstrom and Humphreys, 1998; du Bray et al., 2018). These granitoids may be divided into ~1.49–1.41 Ga and ~1.41–1.34 Ga pulses (Whitmeyer and Karlstrom, 2007). They were interpreted as anorogenic (Anderson and Morrison, 2005; Goodge and Vervoort, 2006). However, episodes of significant deformation and metamorphism are now recognized in parts of New Mexico, Arizona and Colorado at these times of pluton emplacements (Nyman et al., 1994; Kirby et al., 1999; McCoy, 2001; Daniel and Pyle, 2006; Jones et al. 2010; Shah and Bell., 2012; Doe et al., 2013; Mahan et al., 2013; Mako et al., 2015; Aronoff et al., 2016; Lytle, 2016, Bollen et al., 2022; Daniel et al., 2022b,), suggesting a convergent setting.

## The Grenville Orogeny

The ~1.2–1.0 Ga Grenville orogeny along the SE margin of Laurentia resulted in the emplacement of the ~1.1 Ga Pikes Peak Batholith in Colorado, but no significant deformation (Whitmeyer and Karlstrom, 2007; Guitreau et al., 2016). Cambrian rifting in Colorado only occurred in the Wet Mountains, and resulted in REE-rich alkaline intrusive rocks and veins (Armbrustmacher, 1988). Elsewhere, Proterozoic deformation was overprinted by the Late Cretaceous–Eocene Laramide orogeny (e.g., English et al., 2003; Kellogg et al., 2008) and associated mineralization. Paleogene mineralization was concentrated within the Colorado Mineral Belt (Fig. 2) and may or may not have been controlled by Proterozoic structures such as shear zones (Tweto and Simms, 1963; Caine et al., 2010; Chapin, 2012). The latest deformation was localized extension associated with the Oligocene and younger Rio Grande Rift, which trends northward from Socorro, New Mexico to Leadville, Colorado (Olsen et al., 1987; Chapin and Cather, 1994; Caine and Minor, 2009; Minor et al., 2013).

## GEOLOGY OF THE CENTRAL COLORADO FRONT RANGE

Prominent Proterozoic structures of the central Colorado Front Range at the latitude of Denver include at least three generations of folds and the Idaho Springs-Ralston shear zone (IRSZ; Figs. 2, 3). The IRSZ is a NE-trending Proterozoic shear zone that was previously interpreted to extend from the Mount Evans Batholith, ~10 km SE of Idaho Springs, CO, to the eastern margin of the Front Range, ~10 km NNW of Golden, CO (e.g. Kellogg et al., 2008). Madison Bzdok (née Lytle; Lytle, 2016) conducted detailed mapping along the shear zone and concluded that it does not extend farther SW than Virginia Canyon Road, on the north side of Idaho Springs (Figs. 2, 3). NE-trending shear zones of the central Colorado Front Range including the IRSZ were initially interpreted as a suture zone that formed during ~1.8–1.6 Ga accretion of small terranes and island arcs to the Proterozoic Wyoming Craton (Bowring and Karlstrom, 1990; McCoy et al., 2005; Abbott and Cook, 2012). This interpretation was largely based on the presence of tectonic mélange at the St. Louis Lake shear zone, ~40 km NNW of the IRSZ (McCoy, 2001). The Proterozoic shear zones were reactivated between ~1.45 Ga and ~1.38 Ga (McCoy, 2001). These shear zones may or may not have controlled the location of Paleogene mineralization that generally but not exclusively occurred along the Colorado Mineral Belt (Tweto and Sims, 1963; McCoy, 2001). The interpretation of the IRSZ as a Paleoproterozoic suture zone and its interpreted control on the location of the Colorado Mineral Belt has been debated by Caine et al. (2010).

Based on detailed structural mapping, Lytle (2016; Fig. 3) demonstrated that the IRSZ is not as extensive as previously interpreted. Additionally, a lack of pinch outs and offset of major units, as well as similar deformation histories and metamorphic conditions on either side suggest that the IRSZ did not form as a continental suture zone. Along the IRSZ, isoclinal $F_1$ folds are overprinted by $F_2$ folds (Lytle, 2016; Figs. 3, 4). $F_2$ folds NW of the IRSZ have subvertical NE-trending axial planes and plunge shallowly NE. SE of the IRSZ they also plunge shallowly NE, but axial planes dip shallowly ENE. Lytle (2016) developed a model where isoclinal $F_1$ folds are folded by asymmetric NW-side-up meter-scale $F_2$ folds, followed by a several km-scale NE-plunging, NW-dipping $F_3$ folds (Fig. 4). NW-side-down movement along the IRSZ may have been a result of flexural slip on the NW steeply dipping limb of the NE-plunging, NW-dipping $F_3$ fold. U–Pb laser ablation inductively coupled mass spectrometry monazite dates revealed ~1.68 Ga and ~1.43 Ga events, both within and adjacent to the IRSZ. Relationships between microstructures and monazite grains suggest $F_1$ folds formed at ~1.68 Ga and $F_2$ and $F_3$ folding and associated shearing along the IRSZ occurred at ~1.43 Ga. The relationship between shearing and widespread folding at ~1.43 Ga suggests that Mesoproterozoic deformation, and the extent of the Picuris orogeny, was much more extensive than solely reactivation along shear zones, as previously interpreted (Shaw et al. 2001; McCoy et al., 2005).

Mapping and geochronology by Mahatma (2019), Powell (2020) and Shockley (2021) in the Mount Evans and Montezuma areas SE of Idaho Springs indicated that folding in those areas too was partly Paleoproterozoic and partly Mesoproterozoic. Therefore, pervasive folding as a result of the Picuris orogeny affected a large part of the central Colorado front Range. In addition, U–Pb detrital geochronology of a quartzite south of Mount Evans yielded a ~1.43 Ga detrital zircon population (Fig. 5; Mahatma, 2019), indicating that some of the sedimentary rocks were deposited during the Picuris orogeny. The ~1.43 Ga zircon population is interpreted as detrital, and not metamorphic or hydrothermal, because grains show concentric and oscillatory zoning. In addition, some ~1.43 Ga grains show zoned cores with unzoned metamorphic overgrowths that were too narrow to date, but that suggest igneous zircon growth prior to deposition and metamorphism of the quartzite. This is discussed in detail by Mahatma (2019). The quartzite and other stratified rocks were metamorphosed shortly after deposition of the quartzite as indicated by ~1.42 Ga and ~1.39–1.33 Ga metamorphic monazite in pelitic schist in the area (Mahatma, 2019).

## GEOLOGY OF THE WET MOUNTAINS

The Wet Mountains comprise a NW-trending fault-bounded block of primarily Proterozoic rocks (Fig. 6). Metavolcanic and metasedimentary rocks are intruded by Paleo- and Mesoproterozoic igneous rocks. Paleoproterozoic intrusive bodies include the foliated tonalite and granodiorite of the ~1705 Ma Twin Mountain and Crampton Mountain plutons and the weakly foliated to undeformed granodiorite of the ~1663 Ma Garell Peak pluton (Fig. 6; Bickford et al., 1989). Mesoproterozoic intrusive rocks include the foliated 1442–1439 Ma Oak Creek pluton (Figs. 6, 7), which ranges from quartz monzonite and monzogranite to leucogranite (Bickford et al., 1989; Siddoway et al., 2000; Hernández-Montenegro et al., 2019); the unfoliated 1460 Ma West McCoy Gulch leucogranite pluton (Fig. 6; Cullers et al., 1993); and the 1371–1362 Ma San Isabel pluton (Fig. 6), which is a monzogranite to syenogranite that is variably deformed at exposed margins and generally undeformed within the main body of the pluton (Cullers et al., 1992; Jones et al., 2010).

The southern part of the Wet Mountains contains extensive exposures of migmatite gneiss (Figs. 6, 8). The central and southern Wet Mountains host intrusive bodies, including the Oak Creek and San Isabel plutons, and an extensive network of sill and dike intrusions (Jones et al., 2010; Levine et al., 2013). In the Greenhorn Mountain area south and west of the main body of the San Isabel pluton, host rock-intrusion relationships are commonly unclear, because of the extent of migmatization of host rock gneisses and because of the extensive network of centimeter- to meter-scale felsic intrusions (Fig. 8; Jones et al., 2010; Levine et al., 2013). The San Isabel pluton contains magmatic epidote (Cullers et al., 1992), suggesting mid-crustal emplacement depths. Migmatite gneisses at the contact with the Oak Creek pluton record peak metamorphic conditions of ~750 °C and ~7 kbar (Hernández-Montenegro et al., 2019).

Mesoproterozoic deformation, metamorphism, and igneous rock emplacement occurred between ~1.43 Ga and 1.36 Ga and these processes were broadly coeval throughout the range (Siddoway et al., 2000; Jones et al., 2010). In the northern Wet Mountains, Mesoproterozoic deformation overprinted two generations of Paleoproterozoic fabrics, and strain was concentrated in shear zones (Siddoway et al., 2000). In the southern Wet Mountains, researchers interpret that extensive partial melt generation lead to the formation of melt networks that accommodated lower crustal flow in response to regional compressive stresses (Jones et al., 2010; Levine et al., 2013; Searle, 2013; Levine and Rahl, 2021).

The northern part of the Wet Mountains is well known for thorium and other rare earth element (REE) mineralization associated with Cambrian-Ordovician alkaline intrusions, including the McClure Mountain, Gem Park, and Democrat Creek complexes (Fig. 6). These complexes are sequentially cross-cut by lamprophyre, syenite, and carbonatite dikes, and mineralized quartz-barite-thorite veins (Armbrustmacher, 1988; Magnin et al., 2021). REE mineralization occurs predominately within carbonatite dikes, quartz-barite-thorite veins, and hydrothermally altered red syenite dikes (Armbrustmacher, 1988). Alkaline magmatic rocks in the Wet Mountains may have been derived from a mantle melt, likely related to failed intracontinental rifting during the Cambrian-Ordovician (Olson et al., 1977; Larson et al., 1985; McMillan and McLemore, 2004; Magnin et al., 2021).

## FIELD TRIP DESCRIPTION AND STOPS

We will first discuss how the Picuris orogeny reactivated or overprinted earlier structures, and perhaps controlled the location of structures associated with Cambrian rifting, the Cretaceous- Paleogene Laramide orogeny and subsequent Rio Grande Rift, and associated mineralization. Stops 1–7 will give an overview of geology of the central Colorado Front Range, including rocks and deformation associated with the Paleoproterozoic Yavapai/Mazatzal orogenies and the Mesoproterozoic Picuris orogeny, and some of the Cretaceous- Paleogene structures and mineralization associated with the Laramide orogeny. Stops 8 and 9 will also focus on deformation and metamorphism associated with the Paleoproterozoic Yavapai/Mazatzal orogenies and the Mesoproterozoic Picuris orogeny, and with Cambrian REE-bearing magmatic rocks as a result of Cambrian rifting.

## DAY 1. CENTRAL COLORADO FRONT RANGE – INTRODUCTION TO THE PROTEROZOIC YAVAPAI/MAZATZAL AND PICURIS OROGENIES

Leave conference center 7.00 am

Drive 32 miles, 50 minutes (could make 10 minute restroom break along the way, at gas station before field stop)

**Stop 1. Idaho Springs-Ralston shear zone** 8.00-9.30 am; includes introduction talk

Location: 39°47′11″ N, 105°27′57″ W; 2363m elevation

(coordinates at parking location; outcrops are across the road along the NW side to the NW and the SE)

The outcrop shows a variety of schist and gneiss with subvertical NE-trending foliation and steep lineation (Fig. 9). The shear sense is predominantly NW-side-down and locally NW-side up. One biotite-muscovite schist yielded ~1.67 Ga, ~1.63 Ga and ~1.48 Ga in-situ U-Pb LA-ICPMS monazite ages, and another yielded ~1.62 Ga and ~1.44 Ga ages (Lytle, 2016). The ages are consistent with other ages of deformation along the Idaho Springs-Ralston shear zone, and of folds away from the shear zone (Lytle, 2016).

***Questions for discussion***: What are the shear direction and shear sense? Was this shear zone a suture zone or a smaller scale shear zone? How is it related to folding in the area? How would one find out?

Drive 5 miles, 8 minutes (could make 10 minute restroom break along the way, at gas station before field stop; same as before)

**Stop 2. Mesoproterozoic pegmatite along top-to-the-south shear** 9.45-10.15 am

Location: 39°44′47″ N, 105°23′51″ W; 2108m elevation

(coordinates at outcrop; park ~50 m to the north along the east side of the road in the pull-out and walk south)

Southeast of the Idaho Springs-Ralston shear zone there are tens of meter-scale shear structures displaying top-to-the-south ductile-brittle shear along shallowly-north-dipping shear planes. These may be the latest structures associated with the Picuris orogeny, after folding, or they may represent late flexural slip on the SE limb of a NW-dipping anticline during folding associated with the Picuris orogeny. The pegmatite along the shear plane at this stop (Fig. 10A-D) yielded a weighted average of $^{207}Pb/^{206}Pb$ LA-ICPMS ages of 1441 ± 83 (N=4, MSWD = 2.3), with inheritance of primarily 1771 ± 24 Ma grains (N=9, MSWD = 0.55) and as old as 1913 ± 67 Ma (Fig. 10E).

***Questions for discussion***: What is the significance of these shears? Are they related to folding in the area, and to the Idaho Springs-Ralston shear zone on the other 'limb' of the large-scale NW-dipping NE-plunging synform? How would one find out?

Drive 8.5 miles, 15 minutes (restroom on site at the Edgar Mine)

**Stop 3. Edgar Experimental Mine** 10.30 am-12.30 pm

Location: 39°44′50″ N, 105°31′31″ W; 2399m elevation

(coordinates at outcrop; park ~50 m to the north along the east side of the road in the pull-out and walk south)

The Edgar mine, the Colorado School of Mines Experimental Mine (Fig. 11), stems from the "Rush to the Rockies" mining period. In the 1870s, it produced high-grade silver, gold, lead and copper. It is now part of the Colorado School of Mines and an educational laboratory for those learning to find, develop, and process natural resources. In addition to educating Colorado School of Mines' Mining Engineering students, it provides educational tours for the public and school groups.

The oldest rocks are Paleoproterozoic gneiss and schist (Fig. 11C) that are along-strike with and arguably part of the Idaho Springs-Ralston shear zone. However, the mylonite zone that is characteristic of the Idaho Springs-Ralston shear zone ends less than 700 m to the NE, where the last outcrops can be seen on the Virginia Canyon 'Oh-My-God' (for its twists and turns, which are now much less scary than in the past) Road. In Idaho Springs, a zone of NE-trending foliation exists associated with folding at upper amphibolite facies, but no mylonite zone. This led to the conclusion that the Idaho Springs-Ralston shear zone is not a suture zone, but an effect of regional folding (Lytle, 2019; Fig. 4).

Cretaceous-Paleogene quartz veins and mineralization in the mine (Fig. 11D) are close to parallel in and around the Edgar Mine, but on careful inspection they can be seen to crosscut at very low angle.

***Question for discussion***: Is Cretaceous- Paleogene mineralization, magmatism, faulting and veining controlled by Proterozoic structures?

**Lunch** 12.30-1.00 pm (can make this shorter probably)

Pizza at BeauJo's in Idaho Springs.

***Question for discussion***: What is better: thin-crust pizza or Colorado style mountain pie?

Drive 2.5 miles, 7 minutes

**Stop 4. Mega sigma-clast and other shear structures** 1.15-1.30 pm

Location: 39°44′39″ N, 105°29′16″ W; 2281m elevation

Look east on the cliff across the road to find a mega sigma-clast (Fig. 12A) and other large-scale shear structures (Fig. 12B). The shear sense is top to the south, as in stop 2. Structures like this exist throughout this area SE of the Idaho Springs-Ralston shear zone (and elsewhere?) and give something to look at when stuck in ski traffic.

***Question for discussion***: Continue discussion of stop 2. Also, what causes such large-scale structures to form? Is it because of rheology contrast, or because of brittle shear localization, or something else? Where else have you seen such large-scale shear structures?

Drive 7 miles, 12 minutes

**Stop 5. Sheared Mount Evans batholith** 1.45-2.30 pm (probably include)

Location: 39°41′38″ N, 105°37′02″ W; 2689m elevation

This outcrop looks like steeply WNW-dipping sheared rock with NW-side-up movement (Fig. 13) and may have been interpreted as the Idaho Springs-Ralston Shear Zone in the past. However, it is too northerly-trending for that, and foliations and shear zones within ~500m to the SW, S and SE, and on a separate outcrop ~4 km to the SW along West Chicago Creek Road have various orientations. Shear zones are only local here and their significance is not clear and probably minor.

***Questions for discussion***: Why is the Idaho Springs-Ralston Shear Zone here? Does it reactivate earlier NE-trending structures? How does it relate to other NE-trending shear zones of Colorado, some of which are interpreted as suture zones?

**Stop 6. Weakly foliated Mount Evans batholith** 2.40-3.10 pm

Location: 39°42′13″ N, 105°36′29″ W; 2612m elevation

Here, the Mount Evans batholith looks much less deformed than the previous outcrop (Fig. 14A), and has a weak foliation that is more typical for the Mount Evans batholith. The batholith was initially interpreted as having primarily flow foliations (Aleinikoff et al., 1993), but Powell (2020) noted that most foliations dip moderately NW (Fig. 14B) and are probably tectonic. This may imply the latest shortening direction of the Picuris orogeny was NW, while the top-to-the-south ductile brittle structures of stops 3 and 4 imply that is was south-directed. Interestingly, other ~1.4 Ga plutons and other deformed rocks also show evidence for NW-directed shortening in Colorado (Gonzales et al., 1996; Jones et al., 2010; Shah and Bell, 2012), New Mexico (Grambling and Codding, 1982) and Arizona (Doe and Daniel, 2019), while in the Picuris mountains of New Mexico (Daniel et al., 2013) and the Montezuma mining district of Colorado (Shockley, 2021) it is north-directed.

***Questions for discussion***: What was the latest shortening direction of the Picuris orogeny? What might it have been earlier? How does it fit with shortening in New Mexico and Arizona and with shear zone reactivation?

**Stop 7. Folded migmatitic biotite gneiss** 3.20-3.50 pm

Location: 39°42’50″ N, 105°34′48″ W; 2483m elevation

Migmatitic biotite gneiss is isoclinally folded, and subsequently refolded by moderately NE-plunging open to close (NW-side-up?) $F_2$ folds (Fig. 15). The lineation is steep and pre-or syn-$F_2$ folding. This location is along strike with the Idaho Springs-Ralston Shear Zone of stop 1, but here it has died out.

***Questions for discussion***: Why does the Idaho Springs-Ralston Shear Zone die out toward the SW? Is it related to folding (flexural flow)?

Drive 150 miles, 2.5-3.0 hours

Stay overnight in Walsenburg, CO

## DAY 2. WET MOUNTAINS – PROTEROZOIC DEFORMATION AND METAMORPHISM AND CAMBRIAN RIFTING

Drive from Best Western Rambler in Walsenburg, depart 7:15am

Drive ~38 miles, 55-75 min

**Stop 8. Garnet biotite migmatite gneiss**

Parking Location: 37°53'30.73"N, 105° 6'23.85"W; 2670m elevation

Walk ~0.9 miles (heading up in elevation) along the Cisneros Trail

This section of the Cisneros Trail contains semi-continuous outcrop exposure of biotite migmatite gneiss, garnet biotite migmatite gneiss, and amphibolite (Fig. 9). We will walk the first mile of the trail. The Cisneros Trail is a ~10-mile path from this stop location to the San Isabel recreation area. The trail continues past this field trip stop through exposures of granitic sill and dike intrusions. The northern section of the trail passes through the main body of the San Isabel pluton, but exposure is poor. Stop 8 will highlight migmatite textures and mineralogy (Fig. 9). These migmatite outcrops are characteristic of the southern Wet Mountains, where host rock-intrusion relationships are cryptic or obscured.

***Questions for discussion***: What can we interpret from migmatite textures in outcrop about the structural or temporal relationship between partial melt formation and felsic intrusions in the southern Wet Mountains? What might different structural interpretations imply about tectonic models of southwestern North America in the Proterozoic?

Drive from Cisneros trailhead to downtown Westcliffe, CO

Drive 48 miles, ~1 hour, 15 min

Stop for lunch in Westcliffe

Drive from Westcliffe along Oak Creek Grade (County Road 143) to East Bear Trailhead pull-out

Drive 20 miles, ~40 minutes

**Stop 9. Oak Creek pluton**

Parking location: 38° 18' 19.764" N, 105° 15' 16.83" W; 2255m elevation

We will examine a section of the Oak Creek pluton exposed along the road (Fig. 8). The Oak Creek is a foliated Mesoproterozoic pluton with a crystallization age of 1442–1439 Ma (Bickford et al., 1989; Cullers et al., 1993; Jones et al., 2010). Its fabrics are generally concordant with host rock fabrics (Siddoway et al., 2000; Jones et al., 2010). Adjacent host rocks include felsic gneiss, amphibolite, and migmatite gneiss (Siddoway et al., 2000; Jones et al., 2010; Levine et al., 2013; Hernández-Montenegro et al., 2019). The Oak Creek ranges in composition from quartz-monzonite to monzogranite to leucogranite (Bickford et al., 1989; Cullers et al., 1993) and is also ferroan in composition (Cullers et al., 1993; Frost et al., 2001; Hernández -Montenegro et al., 2019).

***Questions for discussion***: How can we reconcile the structural evidence of syntectonic emplacement of this Mesoproterozoic pluton with the ferroan geochemical character of the pluton?

**DISCUSSION**

We conclude this field guide with some thoughts for discussion. Previously, Mesoproterozoic orogenic and other Earth processes have been interpreted as different from those in the Paleoproterozoic, and Neoproterozoic/Phanerozoic (e.g., Bradley et al., 2011; Brown et al., 2020; Spencer et al., 2021; Liu et al., 2022). Here, we give a summary of some of the observations and interpretations. Bradley et al. (2011) compiled various datasets and demonstrated various minima, including the number of passive margins, detrital zircons, greenstone-belt collisions, eclogites, granulites, carbonatites, and orogenic gold. Perhaps the quiescence explains the "Boring Billion" of Holland (2006), which was based on a period of little variation in atmospheric oxygen levels. Brown et al. (2020) observed that T/P ratios of metamorphic rocks were higher in the Mesoproterozoic than at any other time in the Earth's history. High T/P conditions were accompanied by high $^{176}Hf/^{177}Hf$ ratios and low $\delta^{18}O$ values in zircon, indicating more juvenile crust in the Mesoproterozoic (Brown et al., 2020). A high volume of massif-type anorthosites also indicate high T/P conditions and zircon Eu/Eu* ratios indicate thin crust (Spencer et al., 2021). Low T/P ratios in metamorphic rocks are characteristic for plate boundaries, (Liu et al., 2022), suggesting that there were fewer plate boundaries in the Mesoproterozoic than before and after that time. Low T/P rocks are especially characteristic for blueschist and eclogite facies rocks and and associated with subduction. While present in the Paleoproterozoic, these became especially abundant in the Neoproterozoic when there was a transition to modern plate tectonic processes (Brown et al., 2020; Liu et al., 2022).

Paleogeographic reconstructions show that Paleoproterozoic supercontinent may never have broken up fully and transitioned into Rodinia towards the end of the Mesoproterozoic without too much plate movement (e.g. Pisarevsky et al., 2014, Martin et al. 2020). Along the SE margin of Laurentia, there may have been subduction during most of the Mesoproterozoic, and perhaps slab rollback, associated juvenile crust formation, and possible accretion of juvenile crust (cf. Brown et al., 2020; Liu et al., 2022; Daniel et al., 2022a). Plate tectonic processes may have slowed down during this period, or alternatively, the Mesoproterozoic may have been characterized by hot, thin, and low orogens (Spencer et al., 2021).

These observations and interpretations may explain why the Picuris orogeny is so difficult to recognize and was largely overlooked until the past decade. It is still difficult to envision what the entire orogenic belt might have looked like, including locations of the arc, fore-arc and back-arc, and other components of the orogenic belt. We will discuss these issues during the trip, and hope we will have inspiring discussion about the intricacies of the Mesoproterozoic.

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## REFERENCES CITED

Abbott, L., and Cook, E., 2012, Geology Underfoot along Colorado's Front Range: Montana, Mountain Press Publishing Company, 93 p.

Aleinikoff, J.N., Reed, J.C., and DeWitt, E.H., 1993, The Mount Evans batholith in the Colorado Front Range: Revision of its age and reinterpretation of its structure: Geological Society of America Bulletin, v. 105, p. 791–806, https://doi.org/10.1130/0016-7606(1993)105<0791:TMEBIT>2.3.CO;2.

Allen, J.L., and Shaw, C.L., 2011, Seisomogenic structure of a crystalline thrust fault: fabric anisotropy and coeval pseudotachylyte-mylonitic pseudotachylyte in the Grizzly Creek Shear Zone, Colorado, in Fagereng, A°., Toy, V. G. & Rowland, J. V., eds., Geology of the Earthquake Source: A Volume in Honour of Rick Sibson: Geological Society, London, Special Publications, v. 359, p. 135–151.

Anderson, J.L., and Morrison, J., 2005, Ilmenite, magnetite, and peraluminous Mesoproterozoic anorogenic granites of Laurentia and Baltica: Lithos, v. 80, p. 45–60, https://doi.org/10.1016/j.lithos.2004.05.008.

Armbrustmacher, T.J., 1988, Geology and resources of thorium and associated elements in the Wet Mountains area, Fremont and Custer counties, Colorado: United States Geological Survey Profession Paper 1049, 10.3133/pp1049F

Aronoff, R.F., Andronicos, C.L., Vervoort, J.D., and Hunter, R.A., 2016, Redefining the metamorphic history of the oldest rocks in the southern Rocky Mountains: Geological Society of America Bulletin, v. 128, p. 1207–1227, https://doi.org/10.1130/B31455.1.

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

Bickford, M.E., Shuster, R.D., and Boardman, S.J., 1989, U-Pb geochronology of the Proterozoic volcano-plutonic terrane in the Gunnison and Salida area, Colorado, in

Grambling, J.A., and Tewksbury, B.J., eds., Proterozoic geology of the southern Rocky Mountains: Geological Society of America Special Paper 235, p. 33–48.

Bollen, E.M., Stowell, H.H., Aronoff, R.F., Stotter, S.V., Daniel, C.G., McFarlane, C.R.M., Vervoort, J.D., 2022, Reconciling garnet Lu-Hf and Sm-Nd and monazite U-Pb ages for a prolonged metamorphic event, northern New Mexico: Journal of Petrology, v. 63, doi.org/10.1093/petrology/egac031

Bowring, S.A., and Karlstrom, K.E., 1990, Growth, stabilization, and reactivation of Proterozoic lithosphere in the southwestern United States: Geology, v. 18, p. 1203–1206, doi:10.1130/0091-7613(1990)018<1203:GSAROP>2.3.CO;2.

Bradley D.C., 2008, Passive margins through Earth history: Earth-Science Review, v. 91, p. 1-26.

Brown, M., Johnson, T., Gardiner, N.J., 2020, Plate tectonics and the Archean Earth: Annual Review of Earth and Planetary Sciences, v. 48, p. 291-320.

Bryant, Bruce, Miller, R.D., and Scott, G.R., 1973, Geologic map of the Indian Hills quadrangle, Jefferson County, Colorado: U.S. Geological Survey, scale 1:24,000.

Caine, J.S., and Minor S.A., 2009. Structural and geochemical characteristics of faulted sediments and inferences on the role of water in deformation, Rio Grande Rift, New Mexico. Geological Society of America Bulletin 121, 1325–1340.

Caine, J.S., Ridley, J., and Wessel, Z.R., 2010, To reactivate or not to reactivate – nature and varied behavior of structural inheritance in the Proterozoic basement of the eastern Colorado Mineral Belt over 1.7 billion years of earth history: Geological Society of America Field Guide, v. 18, p. 119-140, doi: 10.1130/2010.0018(06).

Chapin, C.E., 2012, Origin of the Colorado Mineral Belt: Geosphere, v. 8, p. 28—43, doi:10 .1130 /GES00694.1.

Chapin, C.E., and Cather, S.M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift, in Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, stratigraphy, and tectonic setting: Geological Society of America Special Paper 291, p. 5—25, doi:10 .1130 /SPE291-p5.

Condie, K.C., 1986, Geochemistry and tectonic setting of Early Proterozoic supracrustal rocks in the southwestern United States: Journal of Geology, v. 94, p. 845–864.

Cullers, R.L., Griffi n, T., Bickford, M.E., and Anderson, J.L., 1992, Origin and chemical evolution of the 1360 Ma San Isabel Batholith, Wet Mountains, Colorado: A mid-crustal granite of anorogenic affi nities: Geological Society of America Bulletin, v. 104, p. 316–328, doi: 10.1130/0016-7606(1992)104<0316:OACEOT>2.3.CO;2.

Cullers, R. L., Stone, J., Anderson, J. L., Sassarini, B., and Bickford, M. E., 1993, Petrogenesis of Mesoproterozoic Oak Creek and West McCoy Gulch plutons, Colorado: An example of cumulate unmixing of a mid-crustal, two mica granite of anorogenic affinity: Precambrian Research, v. 62, p. 139–169.

Daniel, C.G., Pfeifer, L.S., Jones, J.V. III, and McFarlane, C.M., 2013, Detrital zircon evidence for non-Laurentian provenance, Mesoproterozoic (ca. 1490-1450 Ma) deposition and orogenesis in a reconstructed orogenic belt, northern New Mexico, USA: Defining the Picuris orogeny: Geological Society of America Bulletin, v. 125, n. 9-10, p. 1423-1441.

Daniel, C.G., Aronoff, R., Indares, A.D., and Jones, J.V. III, 2022a, Laurentia in transition during the Mesoproterozoic: observations and speculation on the ca. 1500-1340 Ma tectonic evolution of the south Laurentian margin, in Whitmeyer, S.J., Williams, M.L., Kellett, D.A., and Tikoff, B., eds., Laurentia: Turning Points in the Evolution of a Continent: Geological Society of America Memoir 220, https://doi.org/10.1130/2022.1220(08)

Daniel, C.G., Indares, A., Medaris, L.G., Jr., Aronoff, R., Malone, D., and Schwartz, J., 2022b, Linking the Pinware, Baraboo, and Picuris orogenies: Recognition of a trans-Laurentian ca. 1520–1350 Ma orogenic belt, in Whitmeyer, S.J., Williams, M.L., Kellett, D.A., and Tikoff, B., eds., Laurentia: Turning Points in the Evolution of a Continent: Geological Society of America Memoir 220, https://doi.org/10.1130/2022.1220(11).

Daniel, C.G., and Pyle, J.M., 2006, Monazite-Xenotime thermochronometry and $Al_2SiO_5$ reaction textures in the Picuris Range, northern New Mexico, USA: new evidence for a 1450-1400 Ma orogenic event: Journal of Petrology, v. 47, n. 1, p. 97–118.

Doe, M.F., and Daniel, G.G., 2019, Evidence for Mesoproterozoic ca. 1470-1444 Ma regional deformation of the Mazatzal Group and equivalent rocks in the type area of the Mazatzal orogeny, Tonto Basin, Arizona, *in* Pearthree, P.A., ed., Geologic excursions in southwestern North America: Geological Society of America Field Guide 55, p. 1–36, doi.org/10.1130/2019.0055(10).

Doe, M.F., Jones, J.V. III, Karlstrom, K.E., Thrane, K., Frei, D., Gehrels, G., Pecha, M., 2012, Basin formation near the end of the 1.60-1.45 Ga tectonic gap in southern Laurentia: Mesoproterozoic Hess Canyon Group of Arizona and implications for ca. 1.5 Ga super-continent configurations: Lithosphere, v. 4, n. 1, p. 77-88.

Doe, M.F., Jones, J.V. III, Karlstrom, K.E, Dixon, B., Gehrels, G.E., 2013, Using detrital zircon ages and Hf isotopes to identify ca. 1.48-1.45 Ga sedimentary basins and fingerprint potential sources of exotic 1.6-1.5 Ga grains in southwestern Laurentia: Precambrian Research, v. 231, p. 409-421. http://dx.doi.org/10.1016/j.precamres.2013.03.002.

du Bray, E.A., Holm-Denoma, C.S., Lund, K., and Premo, W.R., 2018, Review of the Geochemistry and Metallogeny of Approximately 1.4 Ga Granitoid Intrusions of the Conterminous United States: U.S. Geological Survey Scientific Investigations Report 2017-5111, 34 p., https://doi.org/10.3133/sir20175111.

English, J. M., Johnston, S. T., and Wang, K., 2003, Thermal modelling of the Laramide orogeny: Testing the flat-slab subduction hypothesis: Earth and Planetary Science Letters, v. 214, p. 619–632.,

Frost, B.R., Barnes, C.G., Collins,W.J., Arculus, R.J., Ellis, D.J., Frost, C.D., 2001, A geochemical classification for granitic rocks: Journal of Petrology, v. 42, p. 2033–2048.

Frost, C.D., and Frost, B.R., 2022, Petrologic constraints on the origin of Proterozoic ferroan granites of the Laurentian margin, in Whitmeyer, S.J., Williams, M.L., Kellett, D.A., and Tikoff, B., eds., Laurentia: Turning Points in the Evolution of a Continent: Geological Society of America Memoir 220, https://doi.org/10.1130/2022.1220(10).

Gable, 2000, Geologic map of the Proterozoic rocks of the central Front Range, Colorado: U.S. Geological Survey, IMAP 2605, scale 1:100,000.

Gonzales, D.A., Karlstrom, K.E., and Siek, G., 1996, Syncontractional crustal anatexis and deformation during emplacement of the 1435 Ma Electra Lake gabbro, Needle Mountains, Colorado: The Journal of Geology, v. 104, p. 215–223, doi: 10 .1086 /629815.

Goodge, J.W., and Vervoort, J.D., 2006, Origin of Mesoproterozoic A-type granites in Laurentia: Hf isotope evidence: Earth and Planetary Science Letters, v. 243, p. 711–731, https://doi.org/10.1016/j.epsl.2006.01.040.

Gower, C.F., and Krogh, T.E., 2002, A U-Pb geochronological review of the Proterozoic history of the eastern Grenville Province: Canadian Journal of Earth Sciences, v. 39, p. 795–829, https://doi.org/10.1139/e01-090.

Groulier, P.-A., Indares, A.D., Dunning, G., Mouhksil, A., 2020, Andean style 1.50–1.35 Ga arc dynamics in the southeastern Laurentian margin: the rifting and reassembly of Quebecia: Terra Nova, p. 1-8, doi:10.1111/ter.12482.

Guitreau, M., Mukasa, S.B., Blichert-Tift, J., and Fahnestock, M.F., 2016, Pikes Peak batholith (Colorado, USA) revisited: A SIMS and LA-ICP-MS study of zircon U–Pb ages combined with solution Hf isotopic compositions: Precambrian Research, v. 280, p. 179-194.

Hernández-Montenegro, D., Andronicos, C.L., Zuluaga, C.A., and Aronoff, R.A., 2019, Effects of melt loss, melt retention, and protolith composition on differentiation of anatectic metapelites: A case study of the Wet Mountains, Colorado: Lithos, v. 344–345, p. 425–439, https://doi.org/10.1016/jlithos.2019.06.032.

Holland, H. D., 2006, The oxygenation of the atmosphere and oceans, Philosophical Transactions of the Royal Society B: Biological Sciences, v. 361(1470), p. 903–915. https://doi.org/10.1098/rstb.2006.1838

Holland, M.E., Grambling, T.A., Karlstrom, K.E., Jones III, J.V, Nagotko, K.N., Daniel, C.G., 2020, Geochronologic and Hf-isotope framework of Proterozoic rocks from central New

Mexico, USA: Formation of the Mazatzal crustal province in an extended continental margin arc: Precambrian Research, v. 347, doi:10.1016/j.precamres.2020.105820.

Jessup, M.J., Jones, J.V., Karlstrom, K.E., Williams, M.L., Connelly, J.N., and Heizler, M.T., 2006, Three Proterozoic orogenic episodes and an intervening exhumation evet in the Black Canyon of the Gunnison region, Colorado: The Journal of Geology, v. 114, p. 555-576, doi:10.1086/506160.

Jones, J.V., III, and Connelly, J.N., 2006, Proterozoic tectonic evolution of the Sangre de Cristo Mountains, southern Colorado, U.S.A.: Rocky Mountain Geology, v. 41, p. 79–116, doi: 10.2113/gsrocky.41.2.79.

Jones, J.V., III, Connelly, J.N., Karlstrom, K.E., Williams, M.L., and Doe, M.F., 2009, Age, provenance, and tectonic setting of Paleoproterozoic quartzite successions in the southwestern United States: Geological Society of America Bulletin, v. 121, p. 247–264.

Jones, J.V., III, Siddoway, C.S., and Connelly, J.N., 2010, Characteristics and implications of ca. 1.4 Ga deformation across a Proterozoic mid-crustal section, Wet Mountains, Colorado, USA: Lithosphere, v. 2, p. 119–135, https://doi.org/10.1130/L78.1.

Jones, J.V., III, Daniel, C.G., Frei, D., and Thrane, K., 2011, Revised regional correlations and tectonic implications of Paleoproterozoic and Mesoproterozoic metasedimentary rocks in northern New Mexico, USA: New findings from detrital zircon studies of the Hondo Group, Vadito Group, and Marqueñas Formation: Geosphere, v. 7, no. 4, p. 974–991, https://doi.org/10.1130/GES00614.1.

Karlstrom, K.E., and Bowring, S.A., 1988, Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America: The Journal of Geology, v. 96, p. 561–576.

Karlstrom, K.E., and Humphreys, G., 1998, Influence of Proterozoic accretionary boundaries in the tectonic evolution of western North America: Interaction of cratonic grain and mantle modification events: Rocky Mountain Geology, v. 33, p. 161–179.

Kellog, K.S., Shroba, R.R., Bryant, B., and Premo, W.R., 2008, Geologic map of the Denver west 30' x 60' quadrangle, north-central Colorado: U.S. Geological Survey, scale 1:100,000.

Kirby, E., Karlstrom, K.E., Andronicos, C.L., and Dallmeyer, R.D., 1995, Tectonic setting of the Sandia pluton: An orogenic 1.4 Ga granite in New Mexico: Tectonics, v. 14, p. 185–201, https://doi.org/10.1029/94TC02699.

Kopera, J., 2003, Monazite Geochronology of the Ortega Quartzite: Documenting the Extent of 1.4 Ga Tectonism in Northern New Mexico and across the Orogen [M.S. thesis]: Amherst, University of Massachusetts, 130 p.

Larson, E.E., Patterson, P.E., Curtis, G., Drake, K., Mutschler, F.E., 1985, Petrologic, paleomagnetic, and structural evidence of a Paleozoic rift system in Oklahoma, New Mexico, Colorado, and Utah: Geological Society of America Bulletin, v. 96, n. 11, p. 1364-1372.

Levine, J.S.F. and Rahl, J.M., 2021, Subgrain Boundaries as Sites of Melt Generation and Pathways for Melt Flow: Implications for Rheology From Combined Chemical and Quantitative Orientation Analysis: Journal of Geophysical Research: Solid Earth, v. 126, no. 6, p. e2020JB020487.

Levine, J.S., Mosher, S., Siddoway, C.S., 2013, Relationship between syndeformational partial melting and crustal-scale magmatism and tectonism across the Wet Mountains, central Colorado: Lithosphere v. 5, p. 456–476.

Liu, Y., Mitchell, R.N., Brown, M., Johnson, T.E., and Pisarevsky, S., 2022, Linking metamorphism and plate boundaries over the past 2 billion years: Geology, https://doi.org/10.1130/G49637.1

Lytle, M., 2016, The Proterozoic history of the Idaho Springs-Ralston shear zone: Evidence for widespread ca. 1.4 Ga orogenic event in Central Colorado [M.Sc. thesis]: Golden, Colorado School of Mines, 89 p.

Magnin, B., Kuiper, Y.D., Barkmann, P.E., 2021. Preliminary structural analysis of alkaline dikes and mineralized veins in the Wet Mountains, south-central Colorado: connecting rare earth element mineralization to Cambrian rifting. GSA Abstracts with Programs. Vol 53, No. 6., doi: 10.1130/abs/2021AM-367101

Mahan, K.H., Allaz, J.A., Baird, G.B., and Kelly, N.M, 2013, Proterozoic metamorphism and deformation in the northern Colorado Front Range, *in* Abbott, L.D., and Hancock, G.S., eds., Classic Concepts and New Directions: Exploring 125 Years of GSA Discoveries in the Rocky Mountain Region: Geological Society of America Field Guide, v. 33, p. 185-204, doi:10.1130/2013.0033(06).

Mahatma, A., 2019, The Proterozoic history of the southern half of the Mount Evans 7.5 minute quadrangle: evidence for ca. 1.4 Ga orogenic event in the central Front Range, Colorado: MS Thesis, Colorado School of Mines, Golden CO, 88 p.

Mako, C.A., Williams, M.L., Karlstrom, K.E., Doe, M.F., Powicki, D., Holland, M.E., Gehrels, G., and Pecha, M., 2015, Polyphase Proterozoic deformation in the Four Peaks area, central Arizona, and relevance for the Mazatzal orogeny: Geosphere, v. 11, no. 6, p. 1975–1995, doi:10.1130/GES01196.1.

Martin, E. L., Spencer, C. J., Collins, W. J., Thomas, R. J., Macey, P. H., & Roberts, N. M. W., 2020, The core of Rodinia formed by the juxtaposition of opposed retreating and advancing accretionary orogens: Earth-Science Reviews, v. 211, 103413. https://doi.org/10.1016/j.earscirev.2020.103413

McCoy, A.M., 2001, The Proterozoic ancestry of the Colorado Mineral Belt: ca. 1.4 Ga shear zone system in central Colorado [M.Sc. thesis]: Albuquerque, University of New Mexico, 160 p.

McCoy, A.M., Karlstrom, K.E., Shaw, C.A., and Williams, M.L., 2005, The Proterozoic ancestry of the Colorado Mineral Belt: 1.4 Ga shear zone system in central Colorado, in Karlstrom, K.E., and Keller, G.R., eds., The Rocky Mountain Region: An Evolving Lithosphere: American Geophysical Union Geophysical Monograph 154, p. 71–90, https://doi .org/10.1029/154GM06.

McMillan, N.J., and McLemore, V.T., 2004, Cambrian–Ordovician magmatism and extension in New Mexico and Colorado: New Mexico Bureau of Geology & Mineral Resources Bulletin 160, p. 1-11.

Medaris, L.G. Jr., Singer, B.S., Jicha, B.R., Malone, D.H., Schwartz, J.J., Stewart, E.K., Van Lankvelt, A., Williams, M.L., and Reiners, P.W., 2021, Early Mesoproterozoic evolution of midcontinental Laurentia: Defining the geon 14 Baraboo orogeny: Geoscience Frontiers, v. 12, Article 101174, doi:10.1016/j.gsf.2021.101174.

Minor, S.A., Hudson, M.R., Caine, J.S., Thompson, R.A., 2013, Oblique transfer of -- extensional strain between basins of the middle Rio Grande rift, New Mexico: fault kinematic and paleostress constraints: Geological Society of America Special Paper 494, 345–382.

Nyman, M.W., Karlstrom, K.E., Kirby, E., and Graubard, C.M., 1994, Mesoproterozoic contractional orogeny in western North America: Evidence from ca. 1.4 Ga plutons: Geology, v. 22, p. 901–904, https://doi.org /10.1130/0091-7613(1994)022<0901:MCOIWN>2.3.CO;2.

Olsen, K.H., Baldridge, W.S., Callender, J.F., 1987, Rio Grande rift: an overview: Tectonophysics, v. 143, p. 119–139.

Olson, J.C., Marvin, R.F., Parker, R.L., and Mehnert, H.H., 1977, Age and tectonic setting of lower Paleozoic alkalic and mafic rocks, carbonatites, and thorium veins in south-central Colorado: U.S. Geological Survey Journal of Research, v. 5, p. 673—687

Pedrick, J.N., Karlstrom, K.E., and Bowring, S.A., 1998, Reconciliation of conflicting tectonic models for Proterozoic rocks in northern New Mexico: Journal of Metamorphic Geology, v. 16, p. 687–707, doi:10.1111/j.1525-1314.1998.00165.x.

Pisarevsky, S.A., Elming, S.Å., Pesonen, L.J., and Li, Z.X., 2014, Mesoproterozoic paleogeography: Supercontinent and beyond: Precambrian Research, v. 244, p. 207–225, https://doi.org/10.1016/j.precamres.2013.05.014.

Powell, L., 2020. The Proterozoic geology of the northern half of the Mount Evans 7.5-minute quadrangle. M.S. Thesis, Colorado School of Mines, Golden, CO, USA, 58 pp.

Searle, M., 2013, Crustal melting, ductile flow, and deformation in mountain belts: Cause and effect relationships: Lithosphere, v. 5, no. 6, p. 547-554.

Selverstone, J., Hodgins, M., Aleinikoff, J.N., and Fanning, C.M., 2000, Mesoproterozoic reactivation of a Paleoproterozoic transcurrent boundary in the northern Colorado Front Range: Implications for ~1.7- and 1.4-Ga tectonism: Rocky Mountain Geology, v. 35, p. 139–162, doi: 10.2113/35.2.139.

Shah, A.A., and Bell, T.H., 2012, Ninety million years of orogenesis, 250 million years of quiescence and further orogenesis with no change in PT: Significance for the role of deformation in porphyroblast growth: Journal of Earth System Science, v. 121, no. 6, p. 1365-1399.

Shaw, C.A., Karlstrom, K.E., Williams, M.L., Jercinovic, M.J., and McCoy, A.M., 2001, Electron microprobe monazite dating of ca. 1.71–1.65 Ga and ca. 1.45–1.38 Ga deformation in the Homestake shear zone, Colorado: Origin and early evolution of a persistent intracontinental tectonic zone: Geology, v. 29, no. 8, p. 739–742, doi: 10.1130/0091-7613(2001)029<0739:EMMDOC>2.0.CO;2.

Shaw, C.A., Allen, J.L., 2007, Field rheology and structural evolution of the Homestake shear zone, Colorado: Rocky Mountain Geology, v. 42, n. 1, p. 31-56.

Sheridan, D.M., and Marsh, S.P., 1976, Geologic map of the Squaw Pass quadrangle, Clear Creek, Jefferson, and Gilpin Counties, Colorado: U.S. Geological Survey, scale 1:24,000.

Sheridan, D.M., Reed, J.C., Jr., and Bryant, Bruce, 1972, Geologic map of the Evergreen quadrangle, Jefferson County, Colorado: U.S. Geological Survey, 1:24,000.

Shockley, D., 2021. Proterozoic structural history of the Montezuma mining district in the central Colorado Front Range. M.S. Thesis, Colorado School of Mines, Golden, CO, USA, 101 pp.

Siddoway, C.S., Givot, R.M., Bodle, C.D., and Heizler, M.T., 2000, Dynamic versus anorogenic setting for Mesoproterozoic plutonism in the Wet Mountains, Colorado: Does the interpretation depend on level of exposure?: Rocky Mountain Geology, v. 35, p. 91-111.

Sims, P.K., 1964, Geologic Map of the Central City Quadrangle, Colorado: U.S. Geological Survey, scale 1:24,000.

Sims, P.K., and Gable, D.J., 1964, Geology of Precambrian rocks, Central City district, Colorado: Geological Survey Professional Paper 474-C: Washington, United States Government Printing Office, p. C1-C51.

Spencer, C.J., Mitchell, R.N., Brown, M., 2021, Enigmatic Mid-Proterozoic orogens: hot, thin, and low: Geophysical Research Letters, v. 48, e2021GL093312.

Taylor, 1976, Geologic map of the Black Hawk quadrangle, Gilpin, Jefferson, and Clear Creek Counties, Colorado: U.S. Geological Survey, scale 1: 24,000.

Tucker, R.D., and Gower, C.F., 1994, A U-Pb geochronological framework for the Pinware terrane, Grenville Province, southeast Labrador: The Journal of Geology, v. 102, p. 67–78, https://doi.org/10.1086/629648.

Tweto, O., and Sims, P.K., 1963, Precambrian Ancestry of the Colorado Mineral Belt: Geological Society of America Bulletin, v. 74, p. 991-1014.

Wells, J.D., 1967, Geology of the Eldorado Springs quadrangle, Boulder and Jefferson Counties, Colorado: U.S. Geological Survey Bulletin 1221-D, p. D1-D85, scale 1: 24,000.

Whitmeyer, S.J., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, p. 220–259.

Widmann, B.L., Kirkham, R.M., and Beach, S.T., 2000, Geologic map of the Idaho Springs quadrangle, Clear Creek County, Colorado: Colorado Geological Survey, scale 1: 24,000.

Windley, B.F., 1993, Proterozoic anorogenic magmatism and its orogenic connection: Geological Society [London] Journal, v. 150, p. 39–50.

Wooden, J.L., and DeWitt, E., 1991, Pb isotope evidence for a major Early Proterozoic crustal boundary in western Arizona, *in* Karlstrom, K.E., ed., Proterozoic geology and ore deposits of Arizona: Arizona Geological Society Digest, v. 19, p. 27–50.

Wooden, J.L., Stacey, J.S., Doe, B., Howard, K.A., and Miller, D.M., 1988, Pb isotopic evidence for the formation of Proterozoic crust in the southwestern United States, *in* Ernst, W.G., ed., Metamorphism and crustal evolution of the western United States: Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice Hall, p. 68–86.

Wrucke, C.T., and Wilson, R.F., 1967, Geologic map of the Boulder quadrangle, Boulder County, Colorado: U.S. Geological Survey, scale 1:24,000.

Young, E.J., 1991, Geologic map of the East Portal quadrangle, Boulder, Gilpin, and Grand Counties, Colorado: U.S. Geological Survey, scale 1: 24,000.

**Figure Captions**

Figure 1. Simplified geologic map of Proterozoic age provinces for North America and Proterozoic rocks exposed in the western U.S., (modified from Holland et al., 2020; Daniel et al., 2022a). Dashed black lines indicate the approximate area of the Pinware–Baraboo–Picuris (PBP) Orogen. Abbreviations: Pic–Picuris Mountains; SR–Salt River Canyon.

Figure 2. Simplified map of the southwestern United States showing Proterozoic crustal blocks. Modified after Jones et al. (2010; cf. Condie, 1986; Bennett and DePaolo, 1987; Karlstrom and Bowring. 1988; Wooden et al., 1988; Wooden and DeWitt, 1991). Colorado Mineral Belt indicated with dashed line. After Mahatma (2019).

Figure 3. Geologic map of the Idaho Springs-Ralston shear zone (IRSZ) area from Lytle (2016), after Gable (2000; cf. Sims, 1964; Sims and Gable, 1964; Wells, 1967; Wrucke and Wilson, 1967; Sheridan et al., 1972; Bryant et al., 1973; Sheridan and Marsh, 1976; Taylor, 1976; and Young, 1991). Automated Mineralogy (AM) samples and map areas as described in detail by Lytle (2016) indicated.

Figure 4. Cross section sketch showing proposed deformation and timing of deformation from Lytle (2016). (A) Regional metamorphism at ~1.68 Ga (D1). (B) Picuris orogeny at ~1.45-1.40 Ga (D2). (C) Picuris orogeny at ~1.45-1.40 Ga (D3).

Figure 5. U-Pb LA-ICPMS zircon data from a quartzite (sample 366; Fig. 2). (A) Error ellipses are $2\sigma$ and data that are >10% discordant gray. (B) Relative probability diagram showing

concordant data. (C) Float bar chart with weighted averages of $^{207}Pb/^{206}Pb$ ages for concordant data. (D, E) Field photographs of quartzite looking NE.

Fig. 6. Geologic map of the Wet Mountains after Jones et al. (2010).

Fig. 7. Outcrop photo of the foliated Oak Creek pluton (left) and a photo of stop location 9 (right), with roadside exposure of the Oak Creek pluton.

Fig. 8. Outcrop photos showing typical textures of migmatites in the southern Wet Mountains, including quartz-feldspar migmatite, biotite migmatite, and garnet-biotite migmatite. Note isoclinal, ptygmatic, and refolded folds, shear bands, and anatectic garnet.

Figure 9. Idaho Springs-Ralston shear zone outcrop images.

Figure 10. (A-D) outcrop pictures, showing pegmatite along top-to-the-south shear. C is from Google Earth. (E) U-Pb LA-ICPMS zircon data (error ellipses are 2σ), with weighted averages of $^{207}Pb/^{206}Pb$ ages indicated.

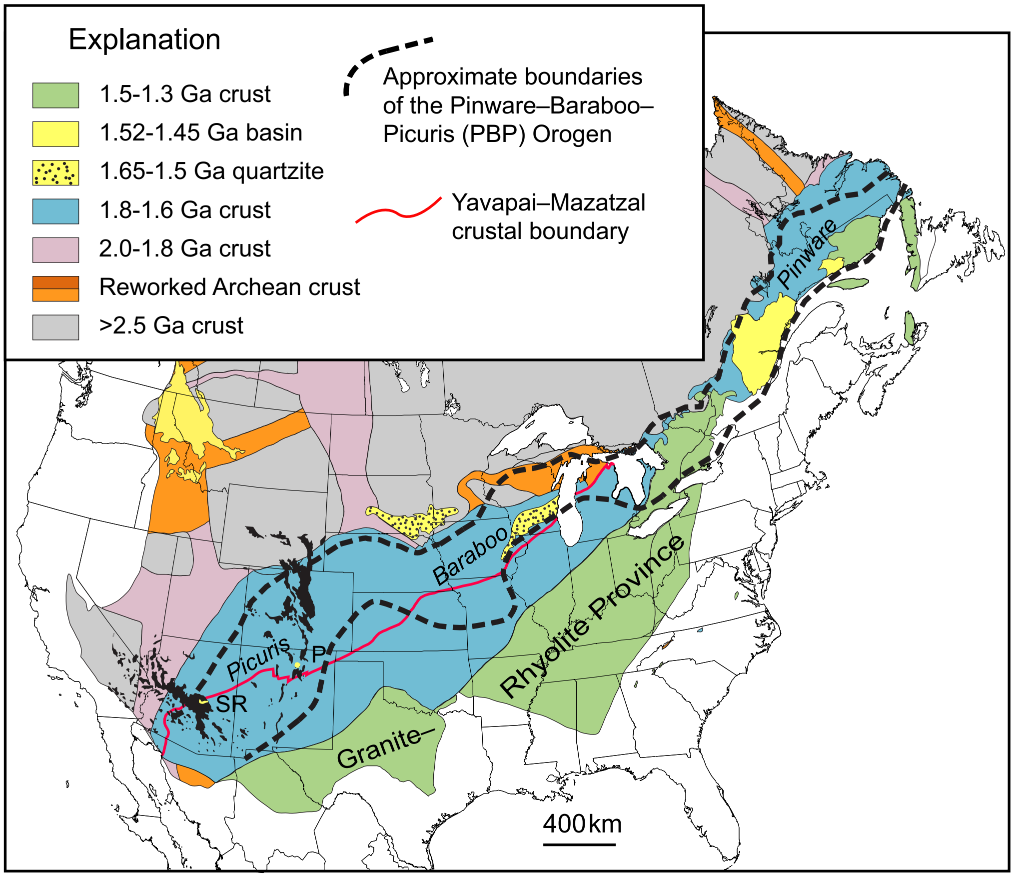
Figure 11. The Edgar Mine, the Colorado School of Mines Experimental Mine. (A) Geology graduate students in front of the entrance. (B) The USGS underground classroom. (C)NW-side-up fold. (D) Pyrite vein. (E) location map of the Edgar Mine (red lines). Quartz-plagioclase gneiss and quartz-plagioclase-biotite gneiss in blue and quartz-biotite-hornblende gneiss and biotite-microcline-pegmatite in brown.

Figure 12. Mega-shear structures indicating top-to-the-south movement.

Fig. 13. (A) Outcrop photo. (B) west-side-up S-C fabric.

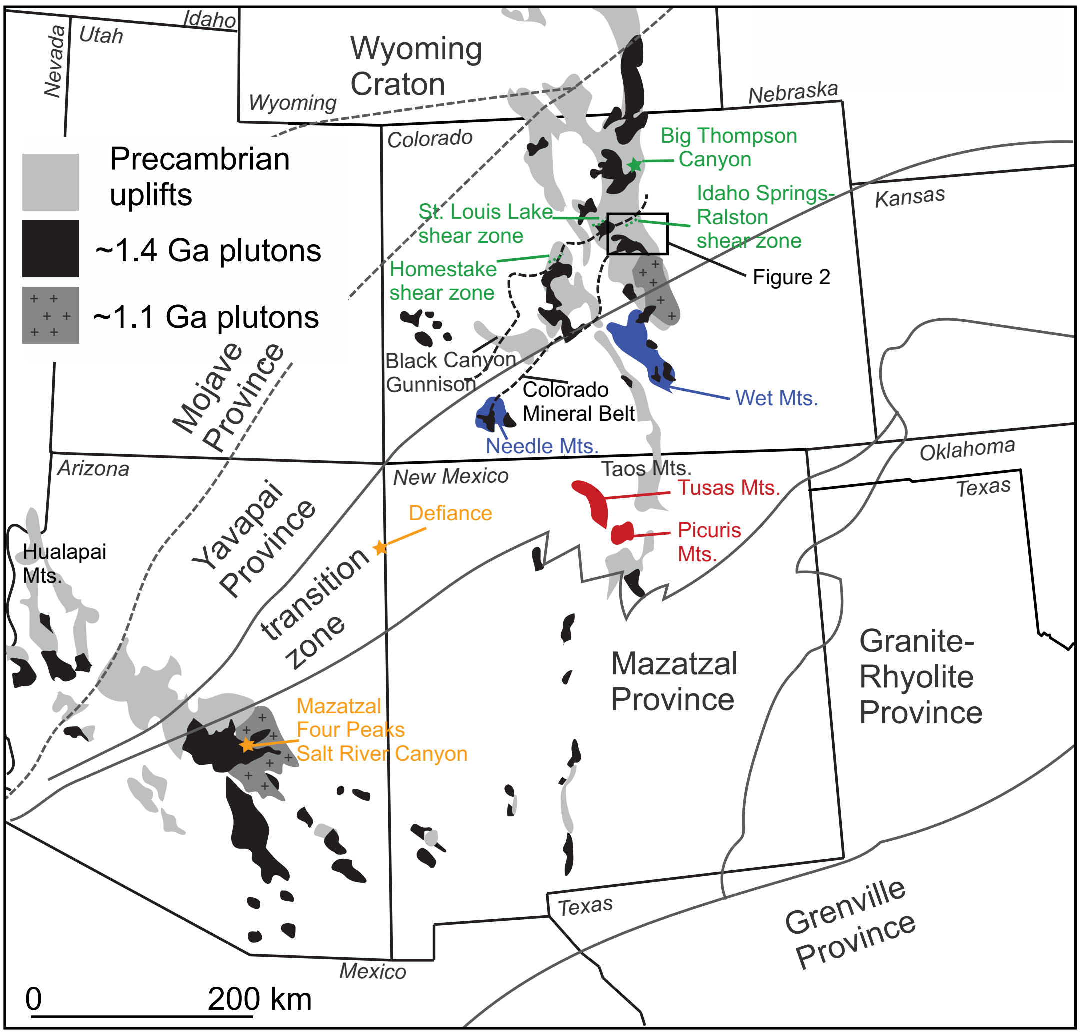
Fig. 14. (A) Outcrop photo, looking SW. (B) Poles to foliation in the Mount Evans batholith at Mount Evans (from Powell, 2020).

Fig. 15. (A) $F_1$ folds in migmatitic biotite gneiss looking down to the NE along an $F_2$ fold hinge. (B) $F_1$ folds in migmatitic biotite gneiss looking down to the NW.



Explanation
1.5-1.3 Ga crust
1.52-1.45 Ga basin
1.65-1.5 Ga quartzite
1.8-1.6 Ga crust
2.0-1.8 Ga crust
Reworked Archean crust
>2.5 Ga crust
Approximate boundaries of the Pinware–Baraboo–Picuris (PBP) Orogen
Yavapai–Mazatzal crustal boundary
Pinware
Baraboo
Picuris
P
SR
Rhyolite Province
Granite–
400 km


Figure 1



Idaho
Utah
Nevada
Wyoming
Wyoming Craton
Nebraska
Colorado
Big Thompson Canyon
Precambrian uplifts
~1.4 Ga plutons
~1.1 Ga plutons
Idaho Springs-Ralston shear zone
Kansas
St. Louis Lake shear zone
Homestake shear zone
Figure 2
Black Canyon Gunnison
Colorado Mineral Belt
Wet Mts.
Mojave Province
Needle Mts.
Oklahoma
Arizona
New Mexico
Taos Mts.
Tusas Mts.
Texas
Defiance
Picuris Mts.
Hualapai Mts.
Yavapai Province
transition zone
Mazatzal Province
Granite-Rhyolite Province
Mazatzal Four Peaks Salt River Canyon
Texas
Grenville Province
Mexico
0
200 km


Figure 2

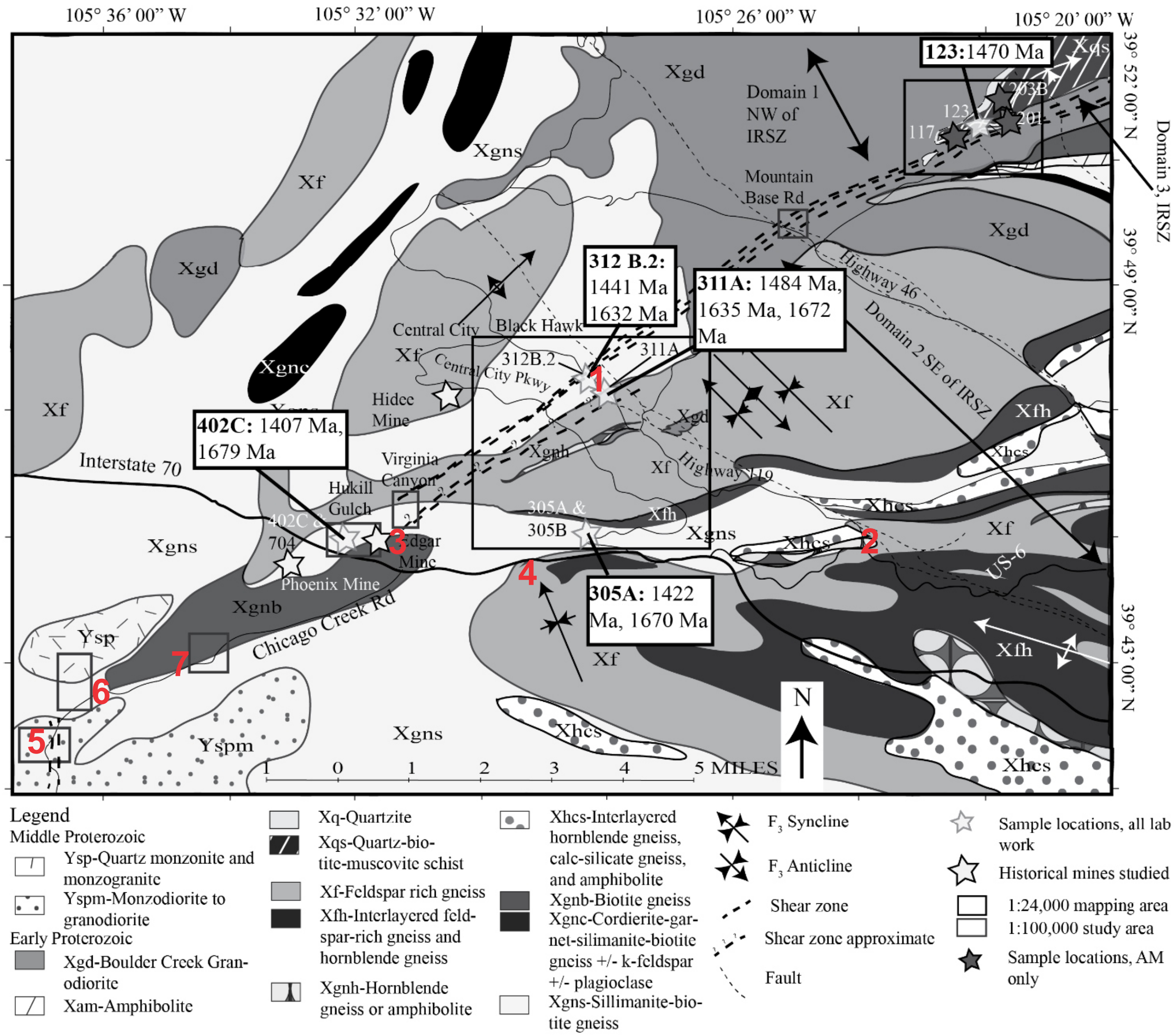
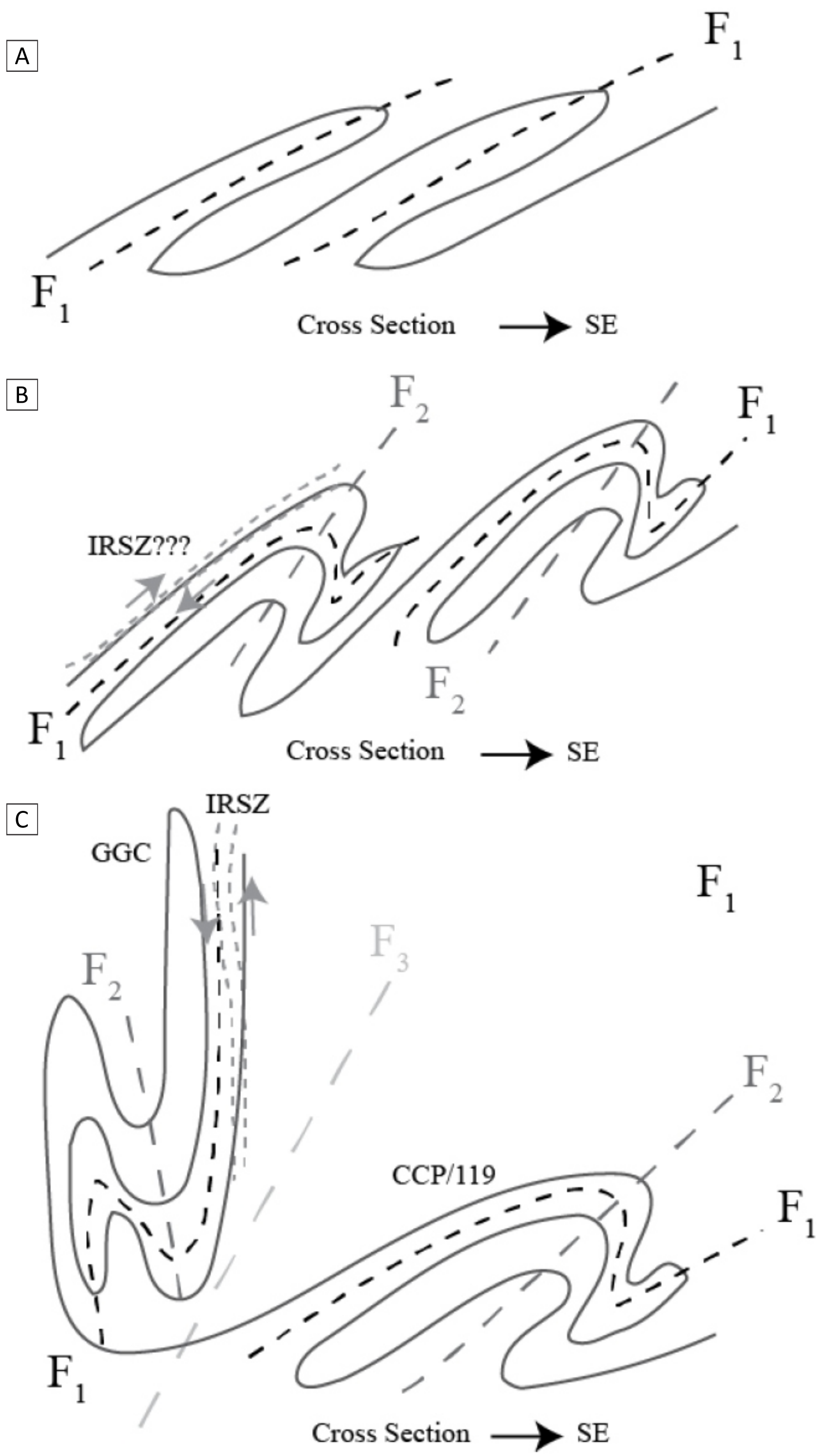

105° 36' 00" W
105° 32' 00" W
105° 26' 00" W
105° 20' 00" W
39° 52' 00" N
39° 49' 00" N
39° 43' 00" N
123:1470 Ma
Domain 1 NW of IRSZ
Domain 3, IRSZ
Domain 2 SE of IRSZ
Mountain Base Rd
Highway 46
312 B.2: 1441 Ma 1632 Ma
311A: 1484 Ma, 1635 Ma, 1672 Ma
402C: 1407 Ma, 1679 Ma
305A: 1422 Ma, 1670 Ma
Central City
Black Hawk
Central City Pkwy
Hidee Mine
Virginia Canyon
Hukill Gulch
Edgar Mine
Phoenix Mine
Interstate 70
Chicago Creek Rd
Highway 119
US-6
Xgd
Xgns
Xf
Xfh
Xhcs
Xgnb
Xgnh
Xgnc
Xqs
Ysp
Yspm
N
1 0 1 2 3 4 5 MILES
Legend
Middle Proterozoic
Ysp-Quartz monzonite and monzogranite
Yspm-Monzodiorite to granodiorite
Early Proterozoic
Xgd-Boulder Creek Granodiorite
Xam-Amphibolite
Xq-Quartzite
Xqs-Quartz-biotite-muscovite schist
Xf-Feldspar rich gneiss
Xfh-Interlayered feldspar-rich gneiss and hornblende gneiss
Xgnh-Hornblende gneiss or amphibolite
Xhcs-Interlayered hornblende gneiss, calc-silicate gneiss, and amphibolite
Xgnb-Biotite gneiss
Xgnc-Cordierite-garnet-silimanite-biotite gneiss +/- k-feldspar +/- plagioclase
Xgns-Sillimanite-biotite gneiss
F3 Syncline
F3 Anticline
Shear zone
Shear zone approximate
Fault
Sample locations, all lab work
Historical mines studied
1:24,000 mapping area
1:100,000 study area
Sample locations, AM only

Figure 3



A
F1
F1
Cross Section → SE
B
F2
F1
IRSZ???
F2
F1
Cross Section → SE
C
IRSZ
GGC
F1
F3
F2
F2
CCP/119
F1
F1
Cross Section → SE


Figure 4

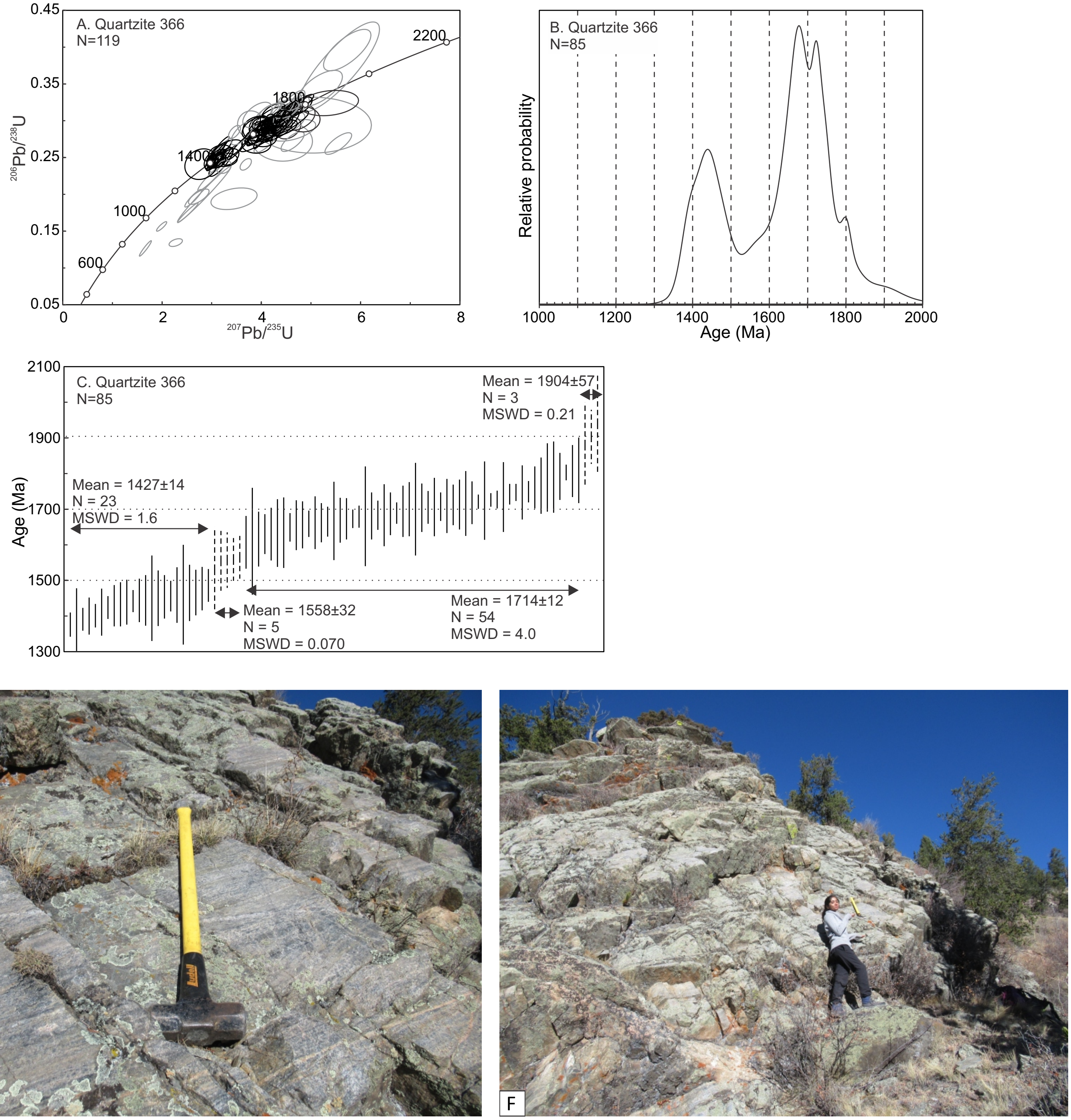
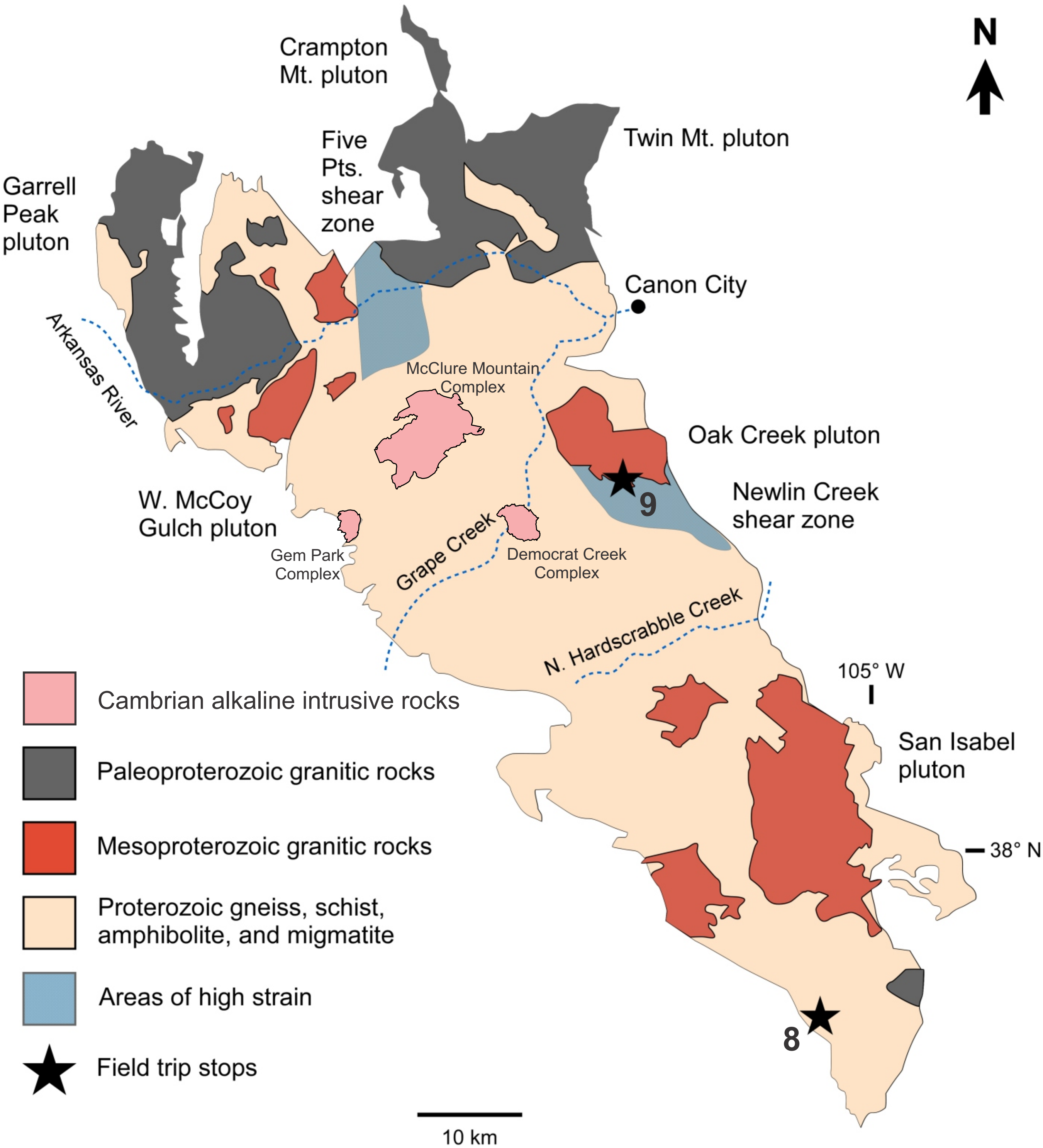

A. Quartzite 366
N=119
0.45
0.35
0.25
0.15
0.05
206Pb/238U
207Pb/235U
0
2
4
6
8
600
1000
1400
1800
2200
B. Quartzite 366
N=85
Relative probability
Age (Ma)
1000
1200
1400
1600
1800
2000
C. Quartzite 366
N=85
Age (Ma)
2100
1900
1700
1500
1300
Mean = 1427±14
N = 23
MSWD = 1.6
Mean = 1558±32
N = 5
MSWD = 0.070
Mean = 1714±12
N = 54
MSWD = 4.0
Mean = 1904±57
N = 3
MSWD = 0.21
E
F

Figure 5



N
Crampton Mt. pluton
Five Pts. shear zone
Twin Mt. pluton
Garrell Peak pluton
Canon City
Arkansas River
McClure Mountain Complex
Oak Creek pluton
9
Newlin Creek shear zone
W. McCoy Gulch pluton
Gem Park Complex
Grape Creek
Democrat Creek Complex
N. Hardscrabble Creek
105° W
San Isabel pluton
38° N
8
Cambrian alkaline intrusive rocks
Paleoproterozoic granitic rocks
Mesoproterozoic granitic rocks
Proterozoic gneiss, schist, amphibolite, and migmatite
Areas of high strain
Field trip stops
10 km


Figure 6

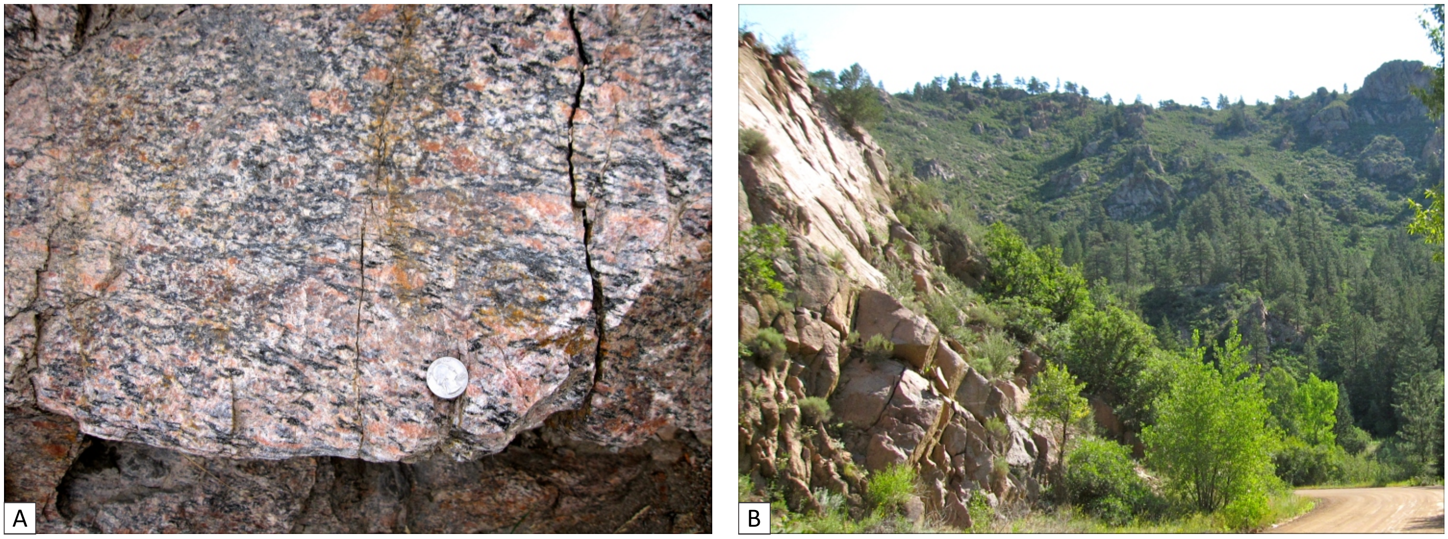



Figure 7

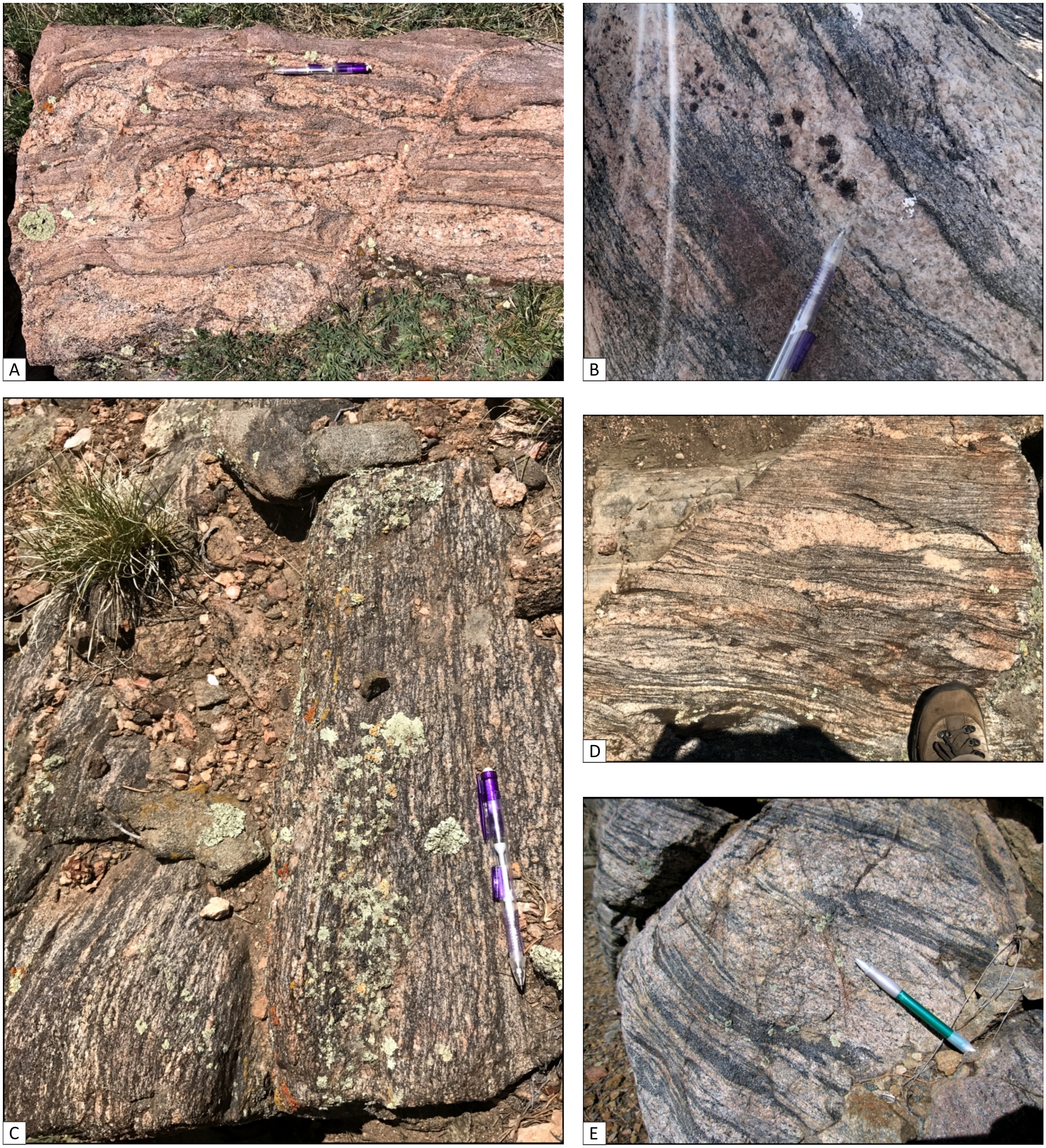



Figure 8

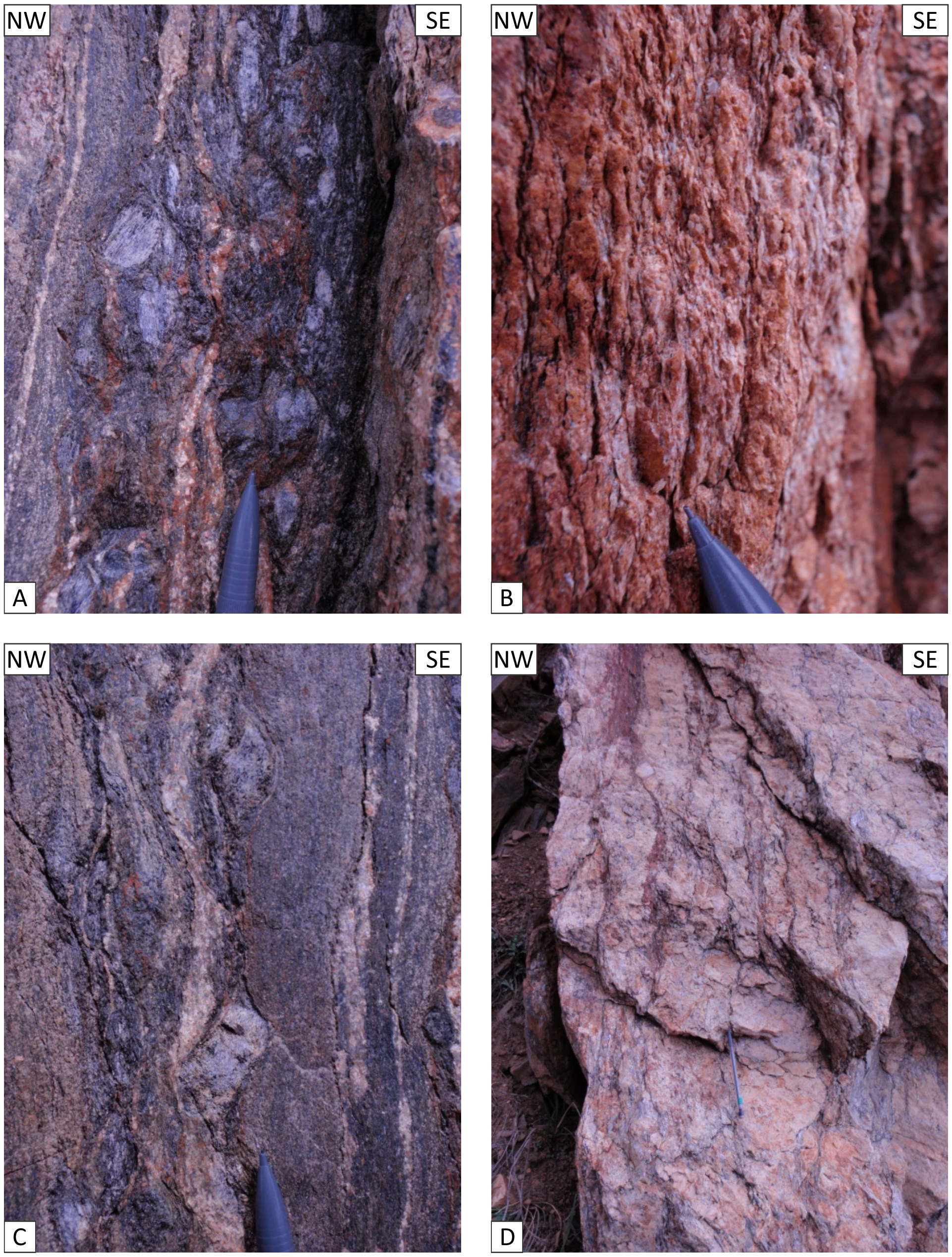



Figure 9

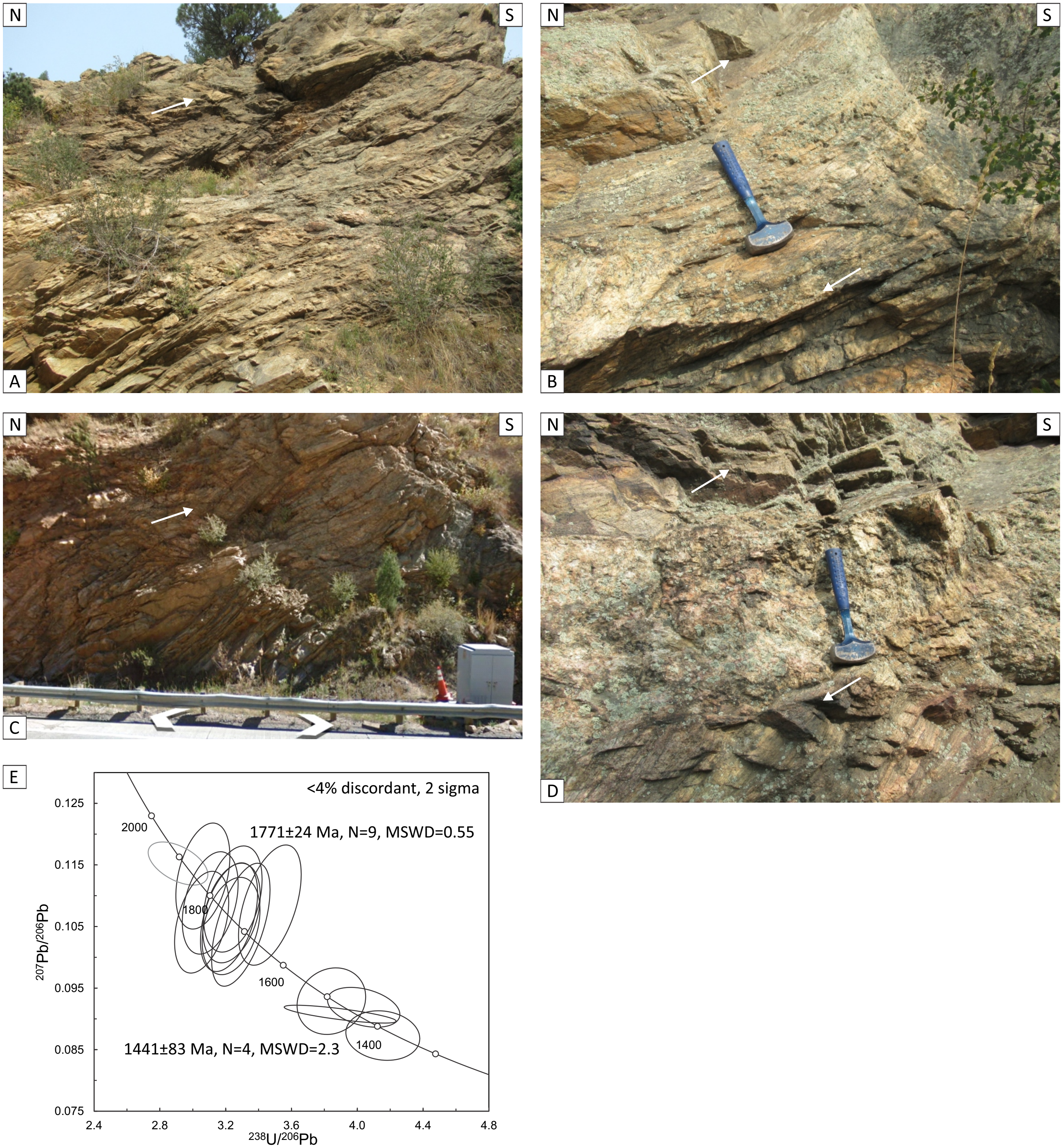

N
S
A
B
C
D
E
<4% discordant, 2 sigma
1771±24 Ma, N=9, MSWD=0.55
1441±83 Ma, N=4, MSWD=2.3
2000
1800
1600
1400
0.125
0.115
0.105
0.095
0.085
0.075
2.4
2.8
3.2
3.6
4.0
4.4
4.8
$^{207}Pb/^{206}Pb$
$^{238}U/^{206}Pb$

Figure 10

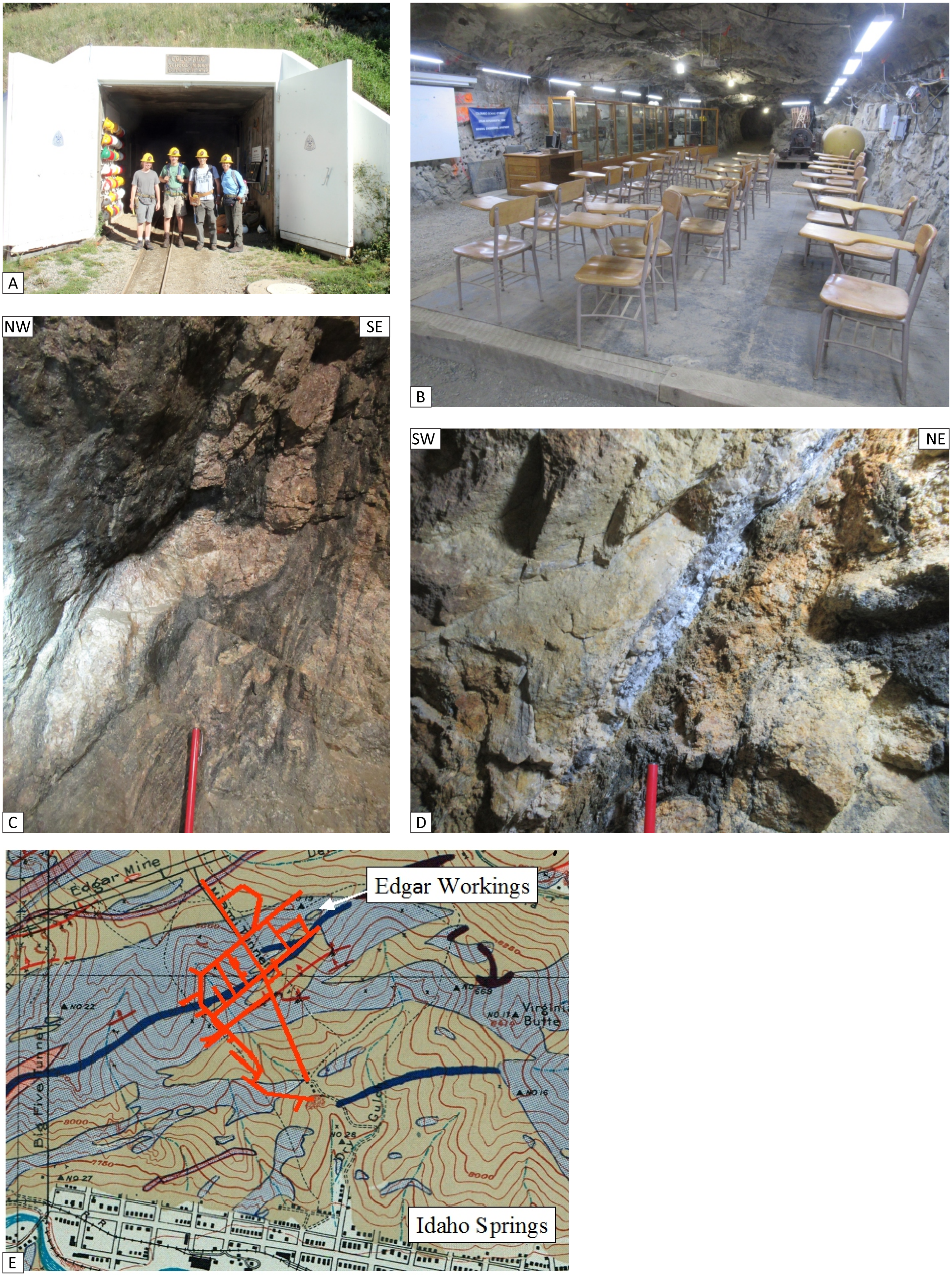

A
NW
SE
C
B
SW
NE
D
Edgar Mine
Edgar Workings
Virginia Butte
Big Five Tunnel
Idaho Springs
E

Figure 11

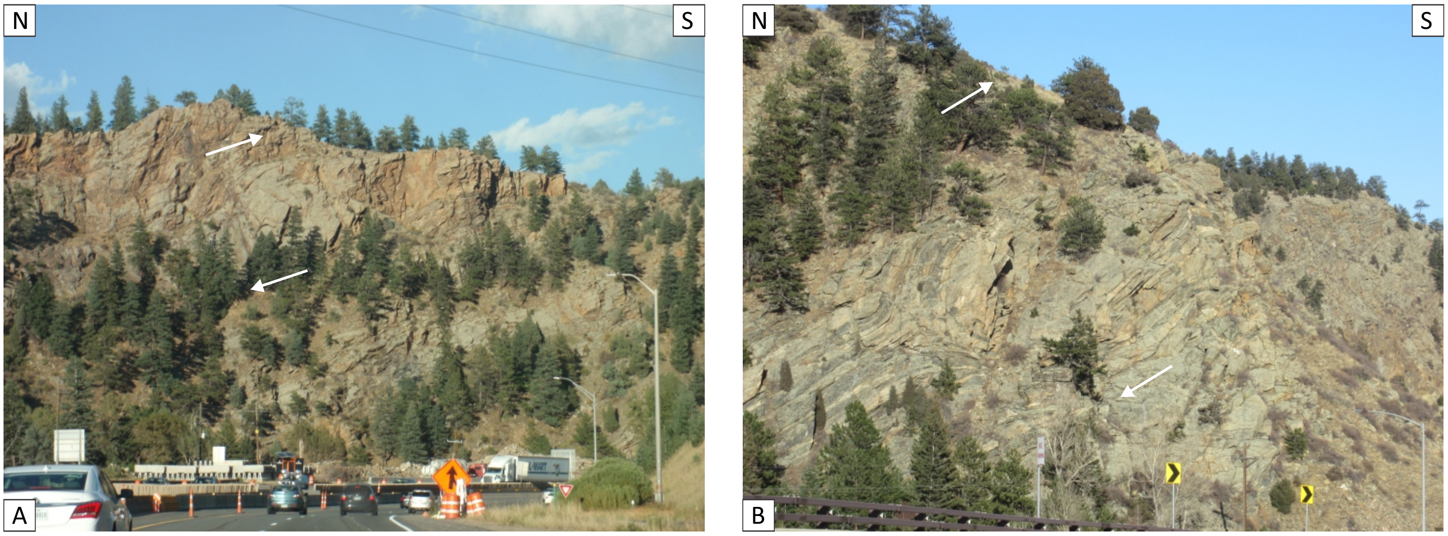



Figure 12


Figure 13

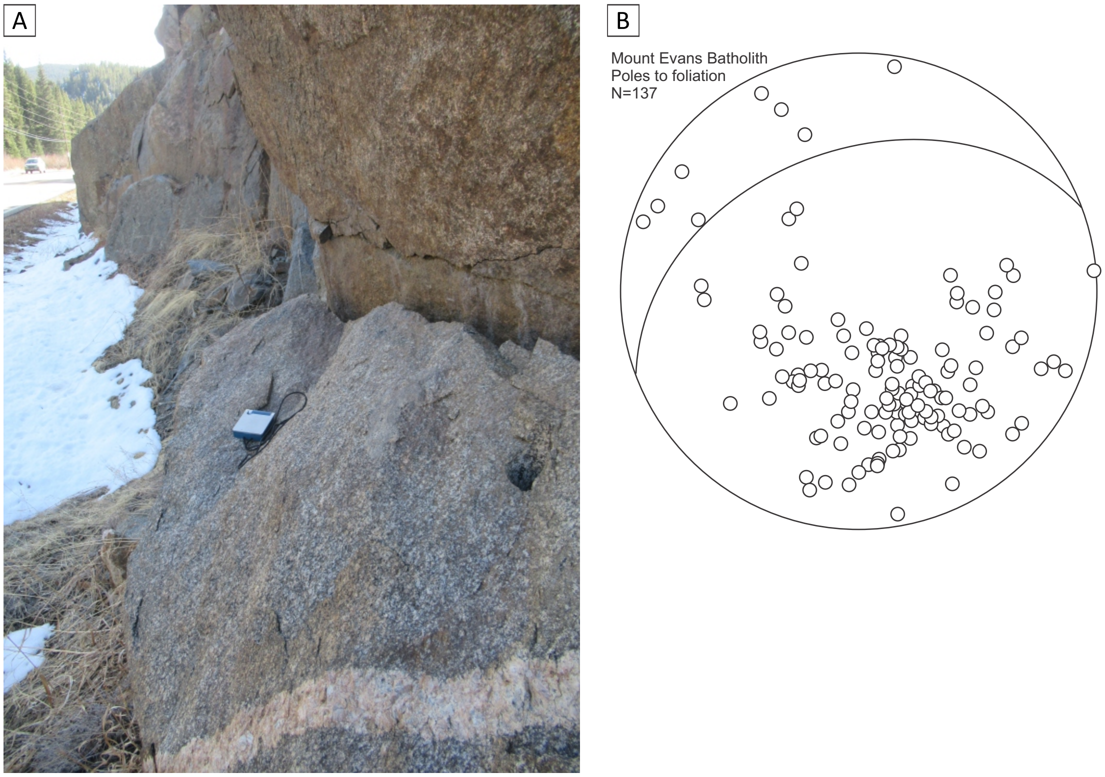



Figure 14

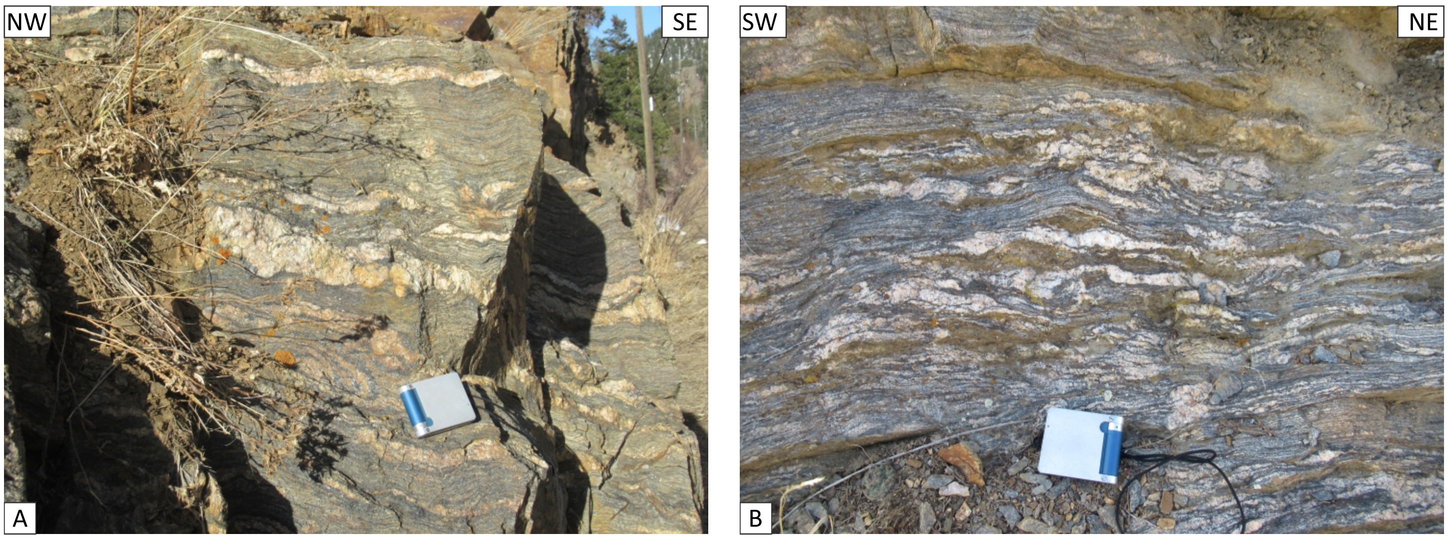



Figure 15