The Proterozoic Ancestry of the Colorado Mineral Belt: 
1.4 Ga Shear Zone System in Central Colorado

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A northeast-striking system of subvertical mylonites and ultramylonites, which formed in the Mesoproterozoic, provided a zone of weakness and conduit for the Paleocene to Oligocene magmatism and mineralization that are the Phanerozoic expressions of the Colorado Mineral Belt. The mylonites overprinted higher temperature Paleoproterozoic high-strain domains of similar orientation. Here, we distinguish the Phanerozoic Colorado Mineral Belt from a Proterozoic ‘Colorado Mineral Belt shear zone system.’ In each segment of the shear zone system, Mesoproterozoic mylonite strands, which are meters to tens of meters wide, overprint higher-temperature Paleoproterozoic high-strain domains, which are several kilometers wide. In situ electron microprobe monazite dating of the mylonites and higher temperature high-strain domains, and field studies of relative timing of shearing and pluton emplacement, show two main periods of shearing that each involve ~100 Ma of deformation. Higher temperature high-strain domains record pulses of deformation that occurred at 1.71-1.69 Ga, 1.67 Ga, 1.65 Ga, and 1.62 Ga. Mylonites record movement at 1.45 Ga synchronous with emplacement of the Mt. Evans pluton, at 1.42 Ga synchronous with emplacement of the Silver Plume pluton, and at 1.38 Ga synchronous with emplacement of the St. Kevin pluton. Post-1.38 Ga movements created ultramylonites. This shear zone system may be analogous to modern-day intracontinental zones of weakness like the Tien Shan of central Asia, which record both original assembly of tectonic blocks and recurrent reactivation during later plate convergence at a distant margin.

1. INTRODUCTION

The Colorado Mineral Belt shear zone system is defined here as a series of northeast-striking mylonitic and ultramylonitic shear zone segments that acted as a coherent shear zone system between 1.45 and 1.38 Ga. Each mylonitic shear zone segment overprints older Paleoproterozoic structures of similar orientation, and although these older structures are present throughout Colorado and are not unique to the Col-
orado Mineral Belt region, their presence suggests a common Paleoproterozoic ancestry to the shear zone system. Along the shear zone system, there is evidence for multiple episodes of reactivation throughout the Proterozoic and the Phanerozoic.

This paper presents a study of the structures, kinematic history, and timing of movement along each shear zone segment, and defines a ‘tectonic fingerprint’ for the shear zone system as a whole. The focus of this paper is to document the Proterozoic Colorado Mineral Belt shear zone system, and to illuminate the initiation and early evolution of this long-lived zone of weakness in the lithosphere.

2. AN INTRACONTINENTAL ZONE OF DEFORMATION FROM THE PROTEROZOIC TO THE PHANEROZOIC

The Colorado Mineral Belt is generally defined as a ~200 kilometer (km) long, northeast-striking zone in central Colorado marked by a concentration of Paleocene to Oligocene intrusions and related mineral deposits emplaced during and after the Laramide orogeny [Figure 1; Tweto and Sims, 1963; Mutschler et al., 1987]. Mining along the Colorado Mineral Belt is famous for having produced billions of dollars worth of gold, silver, lead, zinc, molybdenum, tungsten, and fluor spar [Tweto and Sims, 1963]. The Colorado Mineral Belt is also defined by a pair of negative Bouguer gravity anomalies that are among the most negative in the United States [Figure 1; Isaacson and Smithson, 1976]. Modeling results by McCoy et al. [this volume] and Isaacson and Smithson [1976] suggest that the Colorado Mineral Belt anomaly may be explained in part by large, relatively low-density bodies in the crust, such as granitic batholiths, centered beneath the Colorado Mineral Belt.

The more southerly anomaly is centered on the San Juan Mountains, located along the southwestern extension of the Colorado Mineral Belt. The San Juan Mountains contain middle and late Tertiary (mainly Oligocene) magmatic centers, and its negative Bouguer gravity anomaly is similar to the more northerly anomaly of the Colorado Mineral Belt. Like the Colorado Mineral Belt, the San Juan Mountains show evidence for Proterozoic deformation along steeply-dipping structures [Tweto and Sims, 1963; Baars et al., 1984]. In light of

Figure 1. Map of Bouguer gravity data after Oshetski and Kucks (2001) and McCoy et al. (2001) with Colorado Mineral Belt shear zones, including Homestake, Gore Range, St. Louis Lake, and Idaho Springs-Ralston shear zones. Also shown is Black Canyon shear zone (Jessup et al., 2002) and Laramide magmatism and mining centers.
these similarities, we widen the boundaries of the Colorado Mineral Belt to include the San Juan Mountains [Figure 1].

The irregular geometry of Tweto and Sims’ Colorado Mineral Belt boundaries [1963] does not appear to correspond with mapped structures. In this paper, we use smoother, more general Colorado Mineral Belt boundaries that include the negative gravity anomalies and major mining districts, and lie parallel to the northeast-striking Proterozoic structures [Figure 1].

A number of pieces of evidence suggest that magmatism and deformation of the Phanerozoic Colorado Mineral Belt were localized by the Proterozoic Colorado Mineral Belt shear zone system. First, apatite fission-track studies of Kelley et al. [2001] show that the Colorado Mineral Belt shear zone system coincides with a transition in Laramide-age structural style and timing of uplift in the Front Range. To the south of the shear zone system, Laramide structures are dominated by east-vergent thrusts and Proterozoic rocks have >100 Ma apatite fission-track ages. To the north of the shear zone system, Laramide structures are dominated by southwest-vergent back thrusts and Proterozoic rocks have 76–45 Ma apatite fission-track ages [Kelley et al., 2001]. The discrepancy in ages and structural style across the shear zone suggest that movement along the zone juxtaposed deeper rocks to the north against shallower rocks to the south. Thus, the Colorado Mineral Belt shear system appears to have been reactivated during a protracted period of time in the Laramide, accommodating south-side down differential uplift and exhumation.

Second, stratigraphic studies by Allen [1994] documented multiple Paleozoic movements that directly reactivated at least one of the shear zone segments along the Colorado Mineral Belt shear zone system. The basal conglomerate unit of the Upper Cambrian Sawatch Quartzite thins across strands of the Homestake shear zone from north to south, suggesting that southeast-side up movement occurred along the zone during early stages of Sawatch Quartzite deposition [Allen, 1992]. The Homestake shear zone also coincides with the northern pinch-out of the Lower Ordovician Manitou Dolomite, suggesting southeast-side down reactivation of the Homestake shear zone and erosion prior to deposition of Middle Ordovician Harding Sandstone [Allen, 1993]. Subtle thickness and facies variations in the Upper Devonian Chaffee Group suggest further southeast-side up reactivations [Allen, 1993]. In all, variations in facies and thickness of Paleozoic strata indicate that the Homestake shear zone was reactivated at least four times between Cambrian and late Devonian time, and at least once after Early Mississippian time [Allen, 1994].

Third, tomographic images of Dueker et al. [2001] show a zone of anomalously low-velocity mantle imaged at depths exceeding 120 km that projects upward into the Colorado Mineral Belt, suggesting that this geologic feature is lithospheric in scale and coincides with a modern zone of anomalously low-velocity Proterozoic lithosphere [Dueker et al., 2001]. This suggests continued reactivation of Proterozoic lithosphere compositional domains and/or interfaces during Cenozoic mantle reorganization in the western U.S. [Karlstrom and Humphreys, 1998].

3. THE COLORADO MINERAL BELT SHEAR ZONE SYSTEM

3.1. Previous Work

It has long been argued that the magmatism and mineralization of the Colorado Mineral Belt were localized along pre-existing weaknesses, as indicated by the presence of Proterozoic shear zones and plutons [Tweto and Sims, 1963; Warner, 1978]. We now know that this Precambrian ancestry involved focused deformation and magmatism at ~1.4 Ga and ~1.7 Ga [Shaw et al., 2001], and molybdenite mineralization at ~1.4 Ga [Sims and Stein, 1999]. Although Tweto and Sims [1963] recognized Proterozoic shear zones in the Colorado Mineral Belt, they did not describe the variety of different fault rocks, or ‘tectonites,’ present in the shear zones, nor did they highlight the kinematics of the multiple Proterozoic movements in the shear zones. Tectonites such as cataclasite, ultramylonite, mylonite, and high-temperature striped gneisses, were grouped under the term ‘cataclastic rock.’ Moench [1964] defined two different tectonites along the Idaho Springs-Ralston shear zone, distinguishing the high-temperature gneisses from younger tectonites that resulted from cataclastic deformation of the previously foliated and deformed rocks. Re-examination and re-mapping of the Idaho Springs-Ralston shear zone, as well as other segments of the Colorado Mineral Belt shear zone system, according to a newer understanding of microstructures and kinematic indicators, is presented in this paper.

A recent detailed study by Shaw et al. [2001], which focused on the tectonites, kinematics, and timing of movement in the Homestake shear zone, a segment of the Colorado Mineral Belt shear zone system, sets the stage for this paper. Along the Homestake shear zone, Shaw et al. [2001] showed that transposition of a Paleoproterozoic low-angle S1 fabric was synchronous with granite intrusion and migmatization. This transposed S1 fabric was steepened during the formation of northeast-striking, subvertical S2 high-temperature high strain zones, which were reactivated during the formation of ~1.4 Ga mylonites and ultramylonites. Shaw et al. [2001] used in situ electron microprobe monazite dating to constrain the development or reactivation of S1 at 1700 +/- 7 Ma, movement along S2 at 1658 +/- 5 Ma and 1637 +/- 13 Ma, southeast-side down mylonitization at 1376 +/- 11 Ma, and southeast-side up...
3.2. Map Patterns and Overview of Shear Zone Geometry

The mylonite and ultramylonite shear zone segments of the Colorado Mineral Belt shear zone system lie along the northern edge of the Colorado Mineral Belt between Leadville and Golden, Colorado, and include the Homestake shear zone [Figure 1; Shaw et al., 2001; Allen, 1994; Tweto and Sims, 1963], Gore Range shear zone [Figure 1; Bergendahl, 1969; Tweto and Sims, 1963], St. Louis Lake shear zone [Figure 1; Taylor, 1971; Bryant et al., 1981; Tweto and Sims, 1963], and Idaho Springs-Ralston shear zone [Figure 1; Graubard and Mattinson, 1990; Wells et al., 1964; Tweto and Sims, 1963; Moench, 1964; Sheridan, 1958]. The segments appear to represent en echelon shears, branches of a shear zone system, or even one continuous shear zone (if it was offset by post-Mesoproterozoic dextral fault motions) that extends at least 100 km in length.

At the northeastern extent of its exposure, the Homestake shear zone [Figure 1, Figure 2a] disappears under Phanerozoic cover east of the Eagle River in the northern Sawatch Range. Where Proterozoic rocks surface again, just east of Vail Pass, the Gore Range shear zone [Figure 1, Figure 2b] is directly along strike of the 044°, 79S Homestake shear zone. About 10 km north, and parallel to the Gore Range shear zone, several northeast-striking ultramylonite strands are present at Booth Lake. These strands are considered part of the Colorado Mineral Belt shear zone system, but are not discussed in detail in this paper.

The northeast extent of the Gore Range shear zone segment bends northward to an orientation of 030°, 76W just before it disappears beneath the Phanerozoic cover of the Blue River Valley. If projected across the Blue River Valley and Williams Fork Range at this orientation, the Gore Range shear zone connects with the St. Louis Lake shear zone segment [Figure 1, Figure 2c]. About 10 km east of the St. Louis Lake shear zone, several mylonite strands deform the Silver Plume granite at Berthoud Pass. In this paper, these strands are considered to be part of the St. Louis Lake shear zone because of similar orientations, shear sense, and timing of movement.

The Idaho Springs-Ralston shear zone segment [Figure 1, Figure 2d] does not occur along the strike of the St. Louis Lake shear zone, but is roughly aligned with the trend of the Homestake shear zone. Ancestral Rockies and/or Laramide movements along the north-striking Loveland Pass-Berthoud Pass fault system may have caused dextral strike-slip offset of tens of kilometers between the St. Louis Lake and Idaho Springs-Ralston shear zones.

As part of the current study, we also conducted reconnaissance mapping along the Montezuma shear zone described by Tweto and Sims [1963]. However, the Montezuma shear zone appears to contain only steeply dipping, high-temperature striped gneisses, which are common throughout central Colorado. The zone does not contain composite fabrics including mylonites or ultramylonites, nor does it show any evidence for simple shear, and therefore is not rightly defined as a ‘shear zone’ and is not addressed further in this paper.

3.3. General Characteristics of Shear Zone Segments

In each mylonitic segment of the Colorado Mineral Belt shear zone system, kilometer-wide mylonite zones contain multiple parallel mylonite strands that are one to tens of meters wide. The shear zones also contain ultramylonite strands that are typically narrower than the mylonite strands they overprint. Each mylonitic shear zone segment is northeast-to east-striking, with strikes ranging from 028° to 090°, although the northeast strikes dominate. The shear zone segments are subvertical and dip steeply to the northwest or southeast, with dips ranging from 74°NW to 66° SE. They contain steeply-plunging mineral stretching lineations.

Mylonites and ultramylonites of the Colorado Mineral Belt shear zone system overprint northeast-striking Paleoproterozoic high-strain domains that occur in biotite gneiss and migmatite along the Homestake and Gore Range shear zones [Figs. 2a and 2b]. Along the St. Louis Lake shear zone, the Paleoproterozoic high-strain domains occur in a tectonic melange composed primarily of amphibolite and granodiorite [Figure 2c]. Along Idaho Springs-Ralston shear zone, the high-strain domains occur in quartz monzonite along the southern limb of the Coal Creek synform [Figure 2d].

Although most of the shear zone segments do not appear to separate regions with distinctly different structures or metamorphic histories, they all show juxtaposition of different rock types that hint at the long tectonic evolution of the shear zone system. The shear zones locally follow Paleoproterozoic pluton margins [Figure 2], and show evidence for high temperature deformation synchronous with Paleoproterozoic pluton emplacement [Shaw et al., 2001]. In the Homestake and Gore Range shear zones, relatively high-temperature high strain domains follow the southern margin of the Cross Creek batholith [-1675 [Rb-Sr], Tweto and Lovering, 1977]. In the St. Louis Lake and Idaho-Springs Ralston shear zones, mylonites follow the southern margin of the Boulder Creek batholith [1721 +/- 15 Ma [U-Pb SHRIMP], Premo and Fanning, 2000]. In these high-strain domains, biotite schist is
interlayered and transposed with granite stringers and dikes. Late granite and pegmatite dikes that cut across the foliation suggest that granite intrusion outlasted deformation. Along the Homestake and Gore Range shear zones, there is widespread evidence for migmatization.

The St. Louis Lake shear zone overprints a tectonic melange containing boudinaged rocks of oceanic affinity. The melange contains marble, calc-silicates, possible metamorphosed chert, biotite schist, and amphibolite (including metamorphosed pillow basalts), with boudins of gabbro and ultramafic rocks, all interlayered on the mesoscopic to map scales [Figure 2c]. We interpret these rocks to be parts of a dismembered ophiolite complex tectonically emplaced along the Paleoproterozoic high-strain domains.

The Idaho Springs-Ralston shear zone deforms the Coal Creek Quartzite/pelitic schist sequence, which is one of several isolated Proterozoic meta-quartz arenites in central Colorado [Figure 2d; Finiol, 1992]. These quartzites are
characterized as ‘mature’ from a petrographic standpoint, containing few oxide minerals or micas, and typically deposited on rhyolites or granites.

The mylonite zones also locally follow Mesoproterozoic pluton margins, and show evidence for deformation synchronous with emplacement of these plutons. These mylonite zones also extend tens of kilometers beyond the pluton margins, suggesting that shear zone movement was not isolated along the individual plutons, but was part of a more regional system. In the Homestake shear zone, mylonites follow the northern margin of the Mesoproterozoic St. Kevin batholith [1396 +/- 40 Ma [U-Pb], Doe and Pearson, 1969] and show evidence for syn-plutonic mylonitization [Shaw et al., 2001]. Southeast-side down mylonites deform granite of the St. Kevin batholith, but are also cut by undeformed dikes of St. Kevin granite [Shaw et al., 1999]. Southeast-side up mylonites in the St. Louis Lake and Idaho Springs-Ralston shear zones follow the margins of the Mesoproterozoic Silver Plume pluton [1422 +/- 3 Ma [U-Pb], Hedge, 1969].

At St. Louis Lake, within several meters of the Silver Plume pluton margin, the granite is undeformed, yet the gabbroic country rock has narrow mylonite strands giving southeast-side up shear sense. This field relationship suggests that mylonitization took place before the emplacement of the granite, because the highly competent gabbro is mylonitized whereas the less competent granite is not. At a nearby location, some Silver Plume granite dikes are mylonitized with southeast-side up shear sense, whereas other dikes are undeformed and cross-cut these mylonites, indicating syn-plutonic mylonitization [Figure 2c].

The Idaho Springs-Ralston shear zone follows the margin of the Mt. Evans pluton [1442 +/- 2 Ma [U-Pb], Aleinikoff et al., 1993], and there is field evidence for mylonitization synchronous with pluton emplacement. One strand of the Idaho Springs-Ralston shear zone ends in a series of symmagnetic to late-magmatic subparallel shears in the Mt. Evans pluton and late pegmatites cut mylonitized Mt. Evans granodiorite [Nyman et al., 1994; Graubard and Mattinson, 1990].

3.4. Paleoproterozoic Structures Along the Colorado Mineral Belt Shear Zone System

The shear zone segments are interpreted to have a Paleoproterozoic ancestry because map patterns show close spatial relationships between the Mesoproterozoic mylonite shear zone segments and Paleoproterozoic higher-temperature high-strain domains, Paleoproterozoic plutons, and tectonic melanges. Here, we describe a progression of Paleoproterozoic fabrics and structures observed along each shear zone segment, further supporting the hypothesis of a common Paleoproterozoic ancestry.

Within tens of kilometers of each shear zone segment, shallow to moderately-dipping foliations, typically in migmatised biotite schist, may be observed in kilometer-wide domains. Within a kilometer of each shear zone segment, these shallowly-dipping S1 fabrics are folded into open to isoclinical northeast-striking F2 folds and steepened into northeast-striking, subvertical S2 high-strain domains of intensified foliation. In contrast to the ‘swirling’ foliation patterns described in central Colorado by Reed et al. [1987], our interpretation is that fold interference patterns, created by the folding of S1 by F2 and transposition of S1 into S2 higher temperature high-strain domains, have produced the observed complex map patterns in the Paleoproterozoic rocks along the Colorado Mineral Belt shear zone system.

3.4.1. Regional D1 initially shallowly-dipping foliation and subrecumbent folds. The earliest recognizable fabrics are now represented as composites of pre-D2 transposed foliations, defined as S1a/S1b/S1c in the Homestake and Gore Range shear zones [Shaw et al., 2001], and S1/a/S1b in the St. Louis Lake and Idaho Springs-Ralston shear zones. S1a, an early foliation, is defined by aligned sillimanite needles, elongate biotite, and attenuated quartz and granite stringers. It has been transposed into isoclinal, recumbent F1b folds. In the Homestake and Gore Range shear zones, S1b has been refolded into asymmetric folds with axial plane S1c. These asymmetric folds are of varying tightness, but are always z-shaped in map view, with consistent vergence with respect to the older S1a/b. Granite stringers and migmatisic leucosomes are parallel to S1a/b and also follow the axial plane of S1c [Shaw et al., 2001]. The terminology S1a/S1b/S1c implies that the development of S1 foliation and the transposition of that foliation may have occurred during progressive deformation that created an S1 composite foliation. The sequence of fabrics may record a longer history, but one that has been obscured by the intensity of the latest syn-migmatite deformation.

Adjacent to each shear zone, there is evidence that S1 developed at least in part during granite and granodiorite intrusion associated with emplacement of the Cross Creek (~1675 [Rb-Sr], Tweto and Lovering, 1977) and Boulder Creek [1721 +/- 15 Ma [U-Pb SHRIMP], Premo and Fanning, 2000] batholiths. Magma mingling and cross-cutting relationships also suggest that granodiorite and diorite intruded during Cross Creek granite emplacement, possibly providing a heat source for the observed widespread migmatisation. Unfoliated to weakly foliated post-D1 granite dikes cross-cut S1a/S1b/S1c in a range of orientations along the Homestake and Gore Range shear zones, indicating that granite intrusion outlasted D1.

Along the Idaho Springs-Ralston shear zone, the Coal Creek Quartzite/schist sequence contains bedding within quartzite
that provides a better understanding of the Paleoproterozoic folds and foliation generations. Unlike the migmatites, metavolcanic rocks, and biotite schists along the other shear zone segments, the Coal Creek Quartzite also contains cross bedding that allows determination of stratigraphic younging direction. The Coal Creek Quartzite/schist sequence and granitic rocks of the Boulder Creek batholith both contain an S1 fabric that is parallel to both the metasediment/granite contact and the bedding planes in the quartzite. The metasedimentary rocks show S1a foliation folded into mesoscopic scale F1b isoclinal folds with fold axes that plunge 10 to 35 degrees to the northeast [Figure 3a]. Younging directions in Coal Creek Quartzite, defined by cross beds, alternate from one quartzite layer to the next, suggesting the presence of map-scale folds that, when F2 upright folds are ‘unfolded,’ were probably nearly recumbent [Figure 3].

Along all of the shear zone segments, migmatites with S1 foliation have deformational textures and mineral assemblages that are distinct from the Mesoproterozoic mylonites and ultramylonites that overprint them. Migmatites contain small, recrystallized grains of quartz that are interlocked in polygonal patterns, suggesting that grain boundary area reduction was an important mechanism during the late stages of deformation [Passchier and Trouw, 1996]. Also present are small, recrystallized grains of feldspar. Mineral stretching lineations are typically defined by hornblende needles or sillimanite needles. The observed microstructures and mineral assemblages indicate deformation temperatures that exceeded 500°C [Tullis and Yund, 1992; Spear, 1993].

Along the Homestake and Gore Range shear zones, metamorphic assemblages in migmatites with a strong S1 foliation help define metamorphic conditions during D1. Peak temperature conditions are recorded by the assemblage qtz + biot + garnet + K-feldspar + plag + sill, with prismatic sillimanite oriented within S1. The presence of sillimanite and K-feldspar and the absence of prograde muscovite indicates temperatures above the second sillimanite isograd. The presence of biotite selvages, in which quartz and feldspars are absent and biotite grains have cuspatc edges, suggests the melting reaction albite + K-feldspar + qtz + H₂O -> liquid [Spear, 1993].

3.4.2. D2 high-angle fold and high-strain domain development. Along the Colorado Mineral Belt shear zone system, the S1 composite fabric is folded into F2 folds with northeast-striking axial planes. The enveloping surfaces of F2 folds are subhorizontal, such that unfolding F2 results in the inferred initial low-angle S1 orientations [Moench, 1964]. Open to isoclinal F2 folds with shallowly-plunging fold axes occupy 10- to 100-meter wide macrolithons spaced between subvertical high-strain domains that are tens of meters wide and oriented subparallel to S2 axial plane cleavage. Near these S2 high-strain domains, F2 folds tighten, F2 axial planes steepen, and F2 fold axes become sub-parallel to the steeply-plunging mineral stretching lineations of the high-strain domains. Thus, D2 appears to have resulted in the development of folds as well as high-strain domains. Along the Idaho Springs-Ralston shear zone, the Coal Creek Quartzite/schist sequence and granite are refolded into the
map-scale F2 Coal Creek synform with a northeast-striking, subvertical axial plane and fold axis that plunges shallowly to the northeast [Figure 3b]. At the contact between the Coal Creek Quartzite/schist sequence and Boulder Creek granite, the south limb of the F2 synform sweeps into a northeast-striking, subvertical S2 high-strain domain with steeply-plunging mineral stretching lineations.

We interpret subvertical S2 high-strain domains to have developed during D2, parallel to the axial planes of F2 folds. See Figure 6a for a schematic illustration of D2 fold and high-strain domain development. This is in contrast to the model of Moench [1964], who proposed that high-strain domains along the Idaho Springs-Ralston shear zone reactivated the limb regions of earlier F2 folds.

Along the Gore Range shear zone, some S2 high-strain domains contain asymmetric feldspar augen and melt-filled shear bands that typically indicate southeast-side up shear sense. However, most of the S2 high-strain domains along the Colorado Mineral Belt shear zone system do not give unequivocal shear sense and are mainly distinguished from the migmatites and gneisses of S1 domains by intensified foliations, evidence for grain-size reduction, and stronger mineral stretching lineations.

Kyanite, andalusite, and sillimanite are present together in several thin sections of southeast-side down mylonitized Coal Creek Quartzite, but the growth of all three aluminosilicates occurred prior to Mesoproterozoic mylonitization. Andalusite and kyanite appear to have been brittle boudinaged during mylonitization, and muscovite is present in the boudin necks and forms rims on all of the aluminosilicate minerals [Figure 4d]. In some samples, prismatic andalusite and sillimanite cluster together in ‘knots’ that are wrapped in muscovite. Andalusite and sillimanite appear to be intergrown when present in the same sample, and there is no clear core and rim relationship. Kyanite is always rimmed by andalusite [Figure 4d]. These relationships suggest early kyanite growth followed by a transition from the kyanite stability field to the andalusite or sillimanite stability field (or to the andalusite and then the sillimanite stability field). These rocks, which contain three aluminosilicates, are interpreted to record a looping path near the triple point in P-T space [Figure 4a].

3.5. Timing of Paleoproterozoic Deformation

In situ electron microprobe monazite dating of Paleoproterozoic tectonites in S1 and S2 domains, mylonites, and ultramylonites, allowed constraints to be placed on the timing of deformation along the Colorado Mineral Belt shear zone system. Monazite crystals were located in thin section by conducting full thin section x-ray maps of Ce on the Cameca SX50 electron microprobe at University of Massachusetts, and conducting automated full thin section BSE scans and EDS point analyses on the JEOL scanning electron microscope at the University of New Mexico. X-ray maps of U, Th, Pb, and Y, and spot analyses of U, Th, Pb, and Y, were conducted for selected monazite grains on the Cameca SX50 electron microprobe at the University of Massachusetts and the Cameca SX100 electron microprobe at New Mexico Institute of Mining and Technology.

The in situ electron microprobe monazite dating technique used here is still in the early stages of refinement. The technique is dependent on the fundamental assumptions that monazite incorporates negligible common lead during growth and that elemental concentrations have not been significantly modified by subsequent mass transfer [Montel et al., 1996]. However, it appears that monazite may dissolve and reprecipitate during low-temperature fluid flux events in some mylonite and ultramylonite zones of this study. Despite the problematic aspects of the technique, analyses of the same grains at the University of Massachusetts and the New Mexico Institute of Mining and Technology labs produced statistically similar values, and Williams et al. [1999] show that the electron microprobe monazite dates typically compare closely with mass spectrometric U-Th-Pb dates. For more details on the analyt-
monazite may occur away from a monazite grain during strain, and infill of new textesimal elongation during strain. Matrix minerals may pull These rims or caps typically grow in the direction of infinite-allel to S1 and appears to have overgrown S1, suggesting that direction during strain, to be strong evidence that the age domain is syn-deformational.

Because monazite can grow as a primary igneous mineral, as a hydrothermal mineral during fluid flux, or as a metamorphic mineral during deformational/thermal events, we used several parameters to recognize a monazite grain, or an age domain within a monazite grain, as syn-deformational. When monazite grains were oriented parallel to foliation, we interpreted these grains to be pre- or syn-deformational. Compositional zoning patterns within an age domain are commonly elongate [Plate 1a, Plate 1e]. Although the form of a monazite grain may become elongate through strain-influenced dissolution and reprecipitation during a subsequent deformational event, the compositional zoning is interpreted to be growth zoning within the crystal. The geometry of this compositional zoning is interpreted to reflect the strain field at the time of growth. A monazite grain may rotate during a subsequent deformation, so the elongate grain may come to be aligned within a subsequent foliation. New monazite commonly grows as a rim on an older core [Plate 1b through Plate 1g; Williams et al., 1999; Williams and Jercinovic, 2002]. These rims or caps typically grow in the direction of infinitesimal elongation during strain. Matrix minerals may pull away from a monazite grain during strain, and infill of new monazite may occur [Williams and Jercinovic, 2002]. Thus, we interpret elongate chemical zoning within an age domain in a monazite grain, or a rim age domain that grew in the elongation direction during strain, to be strong evidence that the age domain is syn-deformational.

Based on in situ electron microprobe dating of syn-deformational monazites, parallel to S1 and S2 high-strain domains along the Homestake shear zone, Shaw et al. [2001] defined a period of Paleoproterozoic orogenesis that spanned 1.71 to 1.63 Ga, with deformation pulses at 1700 +/- 7 Ma, 1658 +/- 5 Ma, and 1637 +/- 13 Ma. This pattern is found along the entire length of the Colorado Mineral Belt shear zone system.

In this study, we find that migmatites with S1 foliation folded by an F2 fold along the Gore Range shear zone also record a Paleoproterozoic period of orogenesis, with deformational pulses that coincide with those documented along the Homestake shear zone by Shaw et al. [2001] [Plate 1a]. One monazite grain from a migmatite has an oldest core date of ~1731 Ma, based on several spot analyses, and a rim date of 1619 +/- 24 Ma [Plate 1b]. The ~1731 Ma core is elongate parallel to S1 and appears to have overgrown S1, suggesting that S1 was already developing at about 1.73 Ga. The 1619 Ma rim overgrew oxide and quartz inclusions that are elongate and parallel to S1, and has compositional domains parallel to S1, suggesting that S1 planes were reactivated during deformation (possibly F2 folding) at 1.62 Ga. The cores of several other grains from a migmatite give an average date of 1674 +/- 13 Ma [Plate 1c, Plate 1d]. The rims on these same grains yield 1647 +/- 15 Ma. The ~1.67 Ga cores are elongate parallel to S1, but the relationship of ~1.65 Ga rim geometries to external structures is unclear.

The Idaho Springs-Ralston shear zone also records a Paleoproterozoic orogenic episode that includes at least three deformational pulses. Monazite grains from an S2 domain in biotite schist, adjacent to a mylonite zone along the southwestern section of the Idaho Springs-Ralston shear zone at Chicago Creek, records Paleoproterozoic deformational pulses at 1692 +/- 13 Ma, 1653 +/- 13 Ma, and 1623 +/- 12 Ma [Plate 1e, Plate 1f]. The oldest monazite dates documented along the Idaho Springs-Ralston shear zone are spot analyses of ~1739 Ma, ~1735 Ma, and ~1719 Ma from two small, elongate grains in biotite schist.

Our mapping of the Coal Creek synform did not reveal any cross-cutting relationships between metamorphic mineral domains along the Homestake, Gore Range, and St. Louis Lake shear zones. In contrast to the heavily migmatized metasedimentary rocks intruded by the Cross Creek and Boulder Creek batholiths elsewhere along the Colorado Mineral Belt shear zone system, the Coal Creek Quartzite/schist sequence does not appear to be migmatitic. In several outcrops, the contact between the Coal Creek Quartzite and granite is marked by a probable paleoregolith that grades from quartz monzonite to arkosic quartzite over >15 meters. Thus, we interpret the quartzite to have been deposited on granite, in contrast to the conclusions of Gable [1980] and Wells et al. [1964], who described an intrusive contact with granite intruding the quartzite before or during D1. There may well be more than one age of granite, but the interpretation of quartzite deposited on granite, after the granite was emplaced at about 1.72 Ga, provides further constraints on the timing of D1 and D2 deformation.

In the Coal Creek Quartzite, the youngest detrital zircon grains with Pb/Pb ages of about 1.66 Ga [J.N. Aleinikoff, written communication, 2001] suggest that the S1 foliation in the quartzite and underlying granite developed after 1.66 Ga. The 1.66 Ga detrital zircon ages come from three grains out of a set of 50, so the associated error is large. But if the youngest detrital zircons are 1.66 Ga, then deformation along S1 in the Colorado Mineral Belt shear zone system may have lasted
from at least 1.73 Ga (based on monazite core dates from migmatites along the Gore Range shear zone) to 1.66 Ga.

3.6. Mesoproterozoic Structures of the Colorado Mineral Belt Shear Zone System

One of the major findings of this study is that the mylonites and ultramylonites within the Colorado Mineral Belt shear zone system are distinct from the Paleoproterozoic high-temperature high strain domains that they overprint. They contain microstructures and minerals that record lower temperatures of deformation, they show unequivocal shear sense, and monazites have Mesoproterozoic dates.

Microstructures are one important way to distinguish temperatures and strain rates associated with different types of tectonites in the Colorado Mineral Belt shear zone system. On the microscopic scale, mylonites are dominated by core and mantle structures in quartz. These microstructures indicate that subgrain rotation recrystallization was an important recovery mechanism, and suggest deformation temperatures between 350° and 450°C [Figure 5a; Regime 2 for quartz, Hirth and Tullis, 1994]. Feldspar grains are brittlely deformed and only locally show undulose extinction, indicating deformation temperatures below 500°C [Figure 5b]. Aluminosilicate minerals, such as sillimanite, are absent or interpreted to be metastable in the mylonites, and retrograde chlorite and muscovite are abundant.

Ultramylonites in each shear zone segment contain large ribbon-like quartz grains that have necklaces of tiny recrystallized quartz grains, indicating that grain boundary migration was active and that the ultramylonites deformed at temperatures of approximately 250° to 350°C [Figure 5d; Regime 1-2 for quartz, Hirth and Tullis, 1994]. Feldspars are broken into small pieces that have become rounded during shearing. In ultramylonites, as in mylonites, aluminosilicate minerals are absent or metastable, and retrograde chlorite and muscovite are abundant.

3.7. Shear Sense in Mylonites and Ultramylonites

Mylonites and ultramylonites have strong asymmetric fabrics (S-C and C-‘C’) and quartz porphyroclasts (sigma and delta), indicating a simple shear component during the development of these tectonites [Figure 5c, Figure 5e]. Because each shear zone segment contains steeply-plunging mineral stretching lineations, movements within the zones are interpreted to be primarily dip-slip. The very small strike-slip components, represented by oblique lineations with rakes of 70° to 80°, do not show consistent sense from one shear zone segment to the next, suggesting that strike-slip components may be only locally important. For example, southeast-side down
mylonites in the Homestake and Idaho Springs-Ralston shear zones have small dextral components to movement, but southeast-side down mylonites in the Gore Range shear zone have a small sinistral component.

In each shear zone, ultramylonites appear to overprint mylonites, and show different shear sense than the mylonites they overprint. In the Homestake and Idaho Springs-Ralston shear zones, southeast-side down, subvertical mylonites with strong S-C fabrics and sigma-porphyroclasts are overprinted by southeast-side up, sub-vertical ultramylonites with C-C' fabrics, Reidel shears, sigma-porphyroclasts, and pseudotachylite veins [Shaw et al., 2001]. In the Gore Range shear zone, southeast-side down mylonites are drag-folded with southeast-side up shear sense and overprinted by ultramylonites with quartz ribs that agree with southeast-side up movement [Figure 5f]. At St. Louis Lake, thin southeast-side down ultramylonite bands overprint southeast-side up mylonites with well-developed S-C fabric [Figure 5g]. Because mylonites and ultramylonites along these shear zone segments have distinctly different mineral stretching lineation orientations, different shear sense, and different deformation microstructures, the two fabrics appear to have formed during separate deformation events. In contrast, some mylonites within the shear zones simply grade into ultramylonites in more mica-rich domains, and the two fabrics have similar mineral stretching lineation orientations and shear sense. In these cases, mylonites and ultramylonites could have formed in the same event but at different strain rates.

3.8. Timing of Mesoproterozoic Deformation

Monazite dating and field relationships bear on the timing of multiple Mesoproterozoic episodes of mylonitization and ultramylonitization in the Colorado Mineral Belt shear zone system. Monazites from the mylonite segments yield only Mesoproterozoic dates.

1.45 Ga movements are documented in the Idaho Springs-Ralston shear zone and in the Homestake shear zone. Previous studies have presented field evidence for southeast-side down and slightly sinistral movement along the Idaho Springs-Ralston shear zone during emplacement of the Mt. Evans pluton [Nyman et al., 1994; Graubard and Mattinson, 1990] at 1442 +/- 2 Ma [U-Pb] Aleinikoff et al., 1993]. Shaw et al. [2001] also reported several monazite dates of ~1452 Ma from Homestake mylonites [Plate 1a].

Motion at about 1.42 Ga is recorded in southeast-side up mylonites in the St. Louis Lake and Idaho Springs-Ralston shear zones [Plate 1g]. Field relations in the St. Louis Lake shear zone indicate southeast-side up mylonitization synchronous with emplacement of the Silver Plume pluton [1422 +/- 3 Ma [U-Pb], Hedge, 1969] in the Idaho Springs-Ralston shear zone, monazites in a southeast-side up mylonite also indicate movement at 1422 Ma. In an S2 domain adjacent to a mylonite zone, several monazite grains with Paleoproterozoic core dates have ~1422 Ma rim dates, based on several spot analyses per rim [Plate 1e, Plate 1f]. A monazite grain from the mylonite zone itself has a 1418 +/- 8 Ma core that has an asymmetry concordant with southeast-side up shear sense observed in sigma porphyroclasts and mesoscopic S-C fabrics [Plate 1g].

One monazite grain in the Coal Creek pelitic schist, adjacent to the Idaho Springs-Ralston shear zone, has a date of 1418 +/- 30 Ma and appears to be enclosed in a poikiloblastic andalusite porphyroblast. This association, suggesting that andalusite grew during or after 1.42 Ga deformation, has not been observed elsewhere in the Colorado Mineral Belt shear zone system. However, farther north in the Front Range, andalusite, staurolite, cordierite, and garnet porphyroblasts overprint earlier assemblages, and andalusite grew across Paleoproterozoic fabrics. Based on hornblende 40Ar/39Ar dates [Selverstone et al., 1997; Shaw et al., 1999], these minerals are interpreted to have grown during a relatively low-pressure episode of metamorphism at ~1.4 Ga.

1.38-1.4 Ga movements are recorded in southeast-side down mylonites in the Homestake and Idaho Springs-Ralston shear zones. In the Homestake shear zone, a population of monazite from the >30-meter wide southeast-side down and slightly dextral main mylonite strand gives an average date of 1376 +/- 11 Ma [Shaw et al., 2001]. Along the southern extent of the Homestake, southeast-side down mylonites moved during St. Kevin batholith emplacement at 1396 Ma [U-Pb], Doe and Pearson, 1969].

The Idaho Springs-Ralston shear zone includes a >30-meter wide, southeast-side down and slightly dextral mylonite strand that deforms the contact between the Coal Creek Quartzite and quartz monzonite of the Boulder Creek batholith. A population of small (~15 micron diameter) monazite grains, elongate parallel to fabric and enclosed in recrystallized quartz grains in mylonitized Coal Creek Quartzite, yield an average date of 1384 +/- 14 Ma. One elongate monazite crystal from the Coal Creek pelitic schist adjacent to the mylonite zone yields a date of 1373 +/- 19 Ma, and is boudinaged due to subsequent deformation. Other elongate monazites from the Coal Creek pelitic schist give an average date of 1396 +/- 18 Ma.

Post-1.38 Ga movements are recorded in southeast-side up ultramylonites that overprint southeast-side down mylonites in the Homestake and Idaho Springs-Ralston shear zones. In the Homestake shear zone, monazite within a >30-meter wide southeast-side up ultramylonite strand, which partly overprints a >30-meter wide southeast-side down mylonite strand, do not seem to constrain the timing of ultramylonitization.
Many of the monazite grains yield dates that are similar to those in the overprinted mylonite, and it is possible that no new monazite grew during ultramylonitization [Shaw et al., 2001]. However, the Homestake ultramylonite contains a 1375 +/− 14 Ma monazite grain that is offset along an antithetic bookshelf fault consistent with the southeast-side up shear sense of the ultramylonite strand [Shaw et al., 2001]. This would suggest that ultramylonitization in the Homestake shear zone occurred after 1375 Ma.

In summary, mylonites and ultramylonites of the Colorado Mineral Belt shear zone system appear to record at least four Mesoproterozoic movements spanning from ~1.45 Ga until after 1.38 Ga. 1.45 Ga movements, associated with emplacement of the Mt. Evans pluton, are documented in southeast-side down and slightly sinistral mylonites of the Idaho Springs-Ralston shear zone. Motion at about 1.42 Ga is recorded in southeast-side up mylonites in the St. Louis Lake and Idaho Springs-Ralston shear zones. 1.38–1.4 Ga movements are recorded in southeast-side down mylonites in the Homestake and Idaho Springs-Ralston shear zones. Post-1.38 Ga movements are indicated by southeast-side up ultramylonites that overprint ~1.38 Ga southeast-side down mylonites in the Homestake and Idaho Springs-Ralston shear zones.
4. DISCUSSION

4.1. Tectonic Fingerprint for Deformation Along the Colorado Mineral Belt Shear Zone System

The record of Mesoproterozoic movements documented in mylonites and ultramylonites of the Colorado Mineral Belt shear zone system, and Paleoproterozoic deformation documented in the higher temperature S1 and S2 domains along the shear zone system, provides a ‘tectonic fingerprint’ for the deformational history of the Colorado Mineral Belt shear zone system. This tectonic fingerprint is summarized in Table 1 and Plate 1 and includes a >100 Ma long Mesoproterozoic period of orogenesis that includes deformational pulses at 1378 +/- 17 Ma associated with SE-side down movement and 1419 +/- 18 Ma associated with SE-side up movement, and a >70 Ma long Paleoproterozoic period of orogenesis that includes deformational pulses at 1620 +/- 20 Ma, 1652 +/- 11 Ma, 1674 +/- 13 Ma, and 1692 +/- 13 Ma. These deformational pulses are identified based on distinct date populations within monazite grains of each shear zone. Because a number of monazite dates determined in the present study

Figure 6. a. D1 continental assembly and early intracontinental deformation created low-angle fabrics between 1.73 and 1.66 Ga. Fragments of oceanic lithosphere were transported along thrust structures and imbricated in accretionary prism. D2 folding and shearing along broad, steeply-dipping intracontinental tectonic zone facilitated shortening of the lithosphere between 1.65 and 1.63 Ga. D3 shearing along discrete, steeply-dipping mylonites and ultramylonites, which reactivate D2 tectonic zones, facilitated further shortening of the lithosphere in response to far-field stresses transmitted from a distant convergent margin between 1.42 and 1.3 Ga. b. Summary of movements of mylonites and ultramylonites of Colorado Mineral Belt shear zone system between 1.42 and 1.3 Ga.
are supported by Rb-Sr and U-Th-Pb ages for adjacent syn-
deformational plutons, and there is a regional correspondence
between conventional and microprobe U-Pb monazite dates
[Williams et al., 2002], we interpret monazite age determina-
tions to be accurate representations of the timing of deforma-
tion. We believe there is a sufficiently large dataset to
prefer the interpretation of discrete pulses over the alterna-
tive interpretation that the monazite data document near con-
tinuums of deformation and monazite growth from 1.38–1.45
Ga and 1.62–1.7 Ga.

4.2. A Regional Context for Timing of Deformation Along
the Colorado Mineral Belt Shear Zone System

The multiple periods of Proterozoic deformation along the
Colorado Mineral Belt shear zone system correspond to mag-
matic and orogenic events documented throughout Colorado
and the southwestern U.S., suggesting that movement along the
shear zones reflects responses to large-scale thermal and tec-
tonic events instead of local events, such as the emplacement of individual plutons.

The few 1.73–1.72 Ga dates obtained in the Gore Range
and Idaho Springs-Ralston shear zones may correspond
with emplacement of the Boulder Creek and Rawah
batholiths at 1721 +/- 15 Ma [[U-Pb SHRIMP], Premo and
Fanning, 2000] and 1720 +/- 8 Ma [[U-Pb], Premo and Van
Schmus, 1989], respectively, and an important stage of
regional metamorphism in the northern Front Range
[Barovich, 1986]. 1.73 Ga dates also come from the arc-
like volcanic supracrustal rocks in the Salida-Gunnison
block south of the Colorado Mineral Belt shear zone system
[Bickford and Boardman, 1984], suggesting that deforma-
tion was associated with subduction and arc development at
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1.70 Ga deformation dates in S1 domains of the Colorado
Mineral Belt shear zone system probably correspond to
1.72–1.70 Ga deformation and movement on initially
shallowly-dipping foliations and subrecumbent folds in cen-
tral Arizona, where the Yavapai orogeny involved partitioned
crustal shortening during amalgamation of lithospheric frag-
ments to North America [Karlstrom and Bowring, 1991].
Monazite growth at ~1.67 Ga in the Gore Range shear zone

Table 1: Summary of Age of Deformation and Magmatism, Temperature Constraints, and Shear Sense For
Each Shear Zone Segment, Colorado Mineral Belt Shear Zone System

<table>
<thead>
<tr>
<th>Colorado Mineral Belt shear zone segment (from southwest to northeast)</th>
<th>Paleoproterozoic</th>
<th>Mesoproterozoic</th>
<th>Laramide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>1.70 Ga</td>
<td>1.66 Ga</td>
<td>&lt;1.38 Ga (SE-side up')</td>
</tr>
<tr>
<td>&gt;500°C</td>
<td>1.64 Ga</td>
<td>1.40 Ga (350-450°C)</td>
<td>250-350°C</td>
</tr>
<tr>
<td>Gore Range</td>
<td>1.73 Ga</td>
<td>1.62 Ga</td>
<td>SE-side up'</td>
</tr>
<tr>
<td>&gt;600°C</td>
<td>1.65 Ga</td>
<td>1.42 Ga (350-450°C)</td>
<td>SE-side up'</td>
</tr>
<tr>
<td>1.67 Ga (SE-side up')</td>
<td>550-650°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>St. Louis Lake</td>
<td>1.72 Ga</td>
<td>1.62 Ga</td>
<td>1.34 Ga (SE-side down')</td>
</tr>
<tr>
<td>&gt;500°C</td>
<td>1.65 Ga</td>
<td>1.42 Ga (350-450°C)</td>
<td></td>
</tr>
<tr>
<td>Idaho Springs</td>
<td>1.69 Ga</td>
<td>1.62 Ga</td>
<td>1.36 Ga (SE-side up')</td>
</tr>
<tr>
<td>1.72 Ga</td>
<td>1.65 Ga</td>
<td>1.42 Ga (SE-side up')</td>
<td>76-45 Ma</td>
</tr>
<tr>
<td>1.73 Ga</td>
<td>1.66 Ga</td>
<td>1.38 Ga (SE-side up')</td>
<td>N-side up'</td>
</tr>
<tr>
<td>500-600°C</td>
<td>350-450°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1Monazite ages, shear sense, and cross-cutting relationships reported in Shaw et al., 2001.
2Rb-Sr age of the Cross Creek batholith reported in Tweed and Lovering, 1977.
3Monazite ages, shear sense, and cross-cutting relationships reported in this study.
4U-Pb SHRIMP age of the Boulder Creek batholith reported in Premo and Fanning, 2000.
5U-Pb age of the Silver Plume pluton reported in Hedged, 1969.
6U-Pb age of the Mt. Evans pluton reported in Aleinikoff et al., 1993.
7Deformation temperatures based on quartz and feldspar microstructure and mineral assemblages reported in this study.
8Apatite fission-track ages reported in Kelley et al., 2001.
9U-Pb age of the St. Kevin batholith reported in Dow and Pearson, 1989.
10Youngest 207Pb/206Pb detrital zircon age from Coal Creek Quartzite reported by Aleinikoff, written communication, 2001.
11Shear sense reported in Nyman et al., 1994.
Plate 1. In a., each curve represents frequency distribution for a microprobe monazite date domain based on 4–17 spot analyses. Short bars represent 1–3 spot analyses. Multiple peaks on same baseline represent different date domains in a single crystal. Peaks with same pattern represent grains within the same sample. Long gray bars represent weighted means for date populations that fall within a 95 percent confidence interval in a pooled t-test, and correspond to pulses of monazite growth. In b. through g., electron microprobe elemental concentration maps showing uranium and yttrium zoning and average microprobe U-Pb-Th date for monazites from migmatite adjacent to Gore Range shear zone (b., c., and d.), monazites from biotite schist adjacent to Idaho Springs-Ralston shear zone (e. and f.), and a monazite from mylonite of Idaho Springs-Ralston shear zone (g.)
may have been associated with the Yavapai orogeny or may have been a more local event coinciding with intrusion of the adjacent Cross Creek batholith.

1.65 to 1.62 Ga deformation dates coincide with the Mazatzal orogeny in southeastern Arizona [Karlstrom and Bowring, 1991], where subvertical, northeast-striking fabrics developed during formation of a continental margin batholith above a northwest- or north-dipping subduction system [Selverstone et al., 1999] that has been projected from Arizona across southern Colorado [Shaw and Karlstrom, 1999]. 1.62 Ga deformation dates also correspond to U-Pb zircon dates of 1618 +/- 22 Ma for the Big Creek gneiss of the northern Front. Deformation dates also correspond to U-Pb zircon dates of southern Colorado [Shaw and Karlstrom, 1999]. 1.62 Ga deformation dates also correspond to U-Pb zircon dates of 1618 +/- 22 Ma for the Big Creek gneiss of the northern Front. Deformation dates also correspond to U-Pb zircon dates of southern Colorado [Shaw and Karlstrom, 1999].

Mesoproterozoic movements in the Colorado Mineral Belt shear zone system correspond in time with intrusions emplaced between 1.3 and 1.45 Ga along a belt that spans the southern margins of Laurentia-Baltica [Nyman et al., 1994]. Although the plutons have been described as anorogenic, recent studies have shown evidence for substantial ~1.4 Ga deformation and metamorphism in the vicinity of many plutons [Nyman et al., 1994]. In Colorado and New Mexico, ~1.4 Ga shear zones are moderately- to steeply-dipping and show evidence for syn-magmatic deformation [Nyman et al., 1994; Kirby et al., 1995].

In the northern Front Range of Colorado, the northeast-striking, steeply-dipping Moose Mountain shear zone shows evidence for reverse-sense reactivation synchronous with intrusion of the ~1.4 Ga St. Vrain pluton [Selverstone et al., 2000]. This shear zone is located 50 km north of, and is roughly parallel to, the Idaho Springs-Ralston shear zone. The relationship between the Moose Mountain shear zone, several other northern Colorado shear zones suspected to have been active at ~1.4 Ga, and the Colorado Mineral Belt shear zone system, is not fully understood. The northern Front Range shear zones have not been documented to extend southwest across Colorado, as the Colorado Mineral Belt shear zone system does.

4.3. Tectonic Significance of the Colorado Mineral Belt Shear Zone System

Metamorphic data indicate that Proterozoic rocks exposed in the Colorado Mineral Belt shear zone system were in the middle crust during tectonism, and deformation studies reveal a pattern of progressive overprinting of increasingly narrower, higher strain-rate/lower-temperature tectonites. This suggests that, at any given time, discrete structures at shallower crustal levels may grade into wider, more diffuse zones at deeper crustal levels. Greenschist-grade ultramylonites overprint wider zones of greenschist-grade mylonites, which overprint even wider, amphibolite-grade high strain domains. Each generation of tectonite appears to have caused grain size reduction and weakening along the shear zone system, leaving it prone to further reactivations.

4.3.1. Tectonic significance of Paleoproterozoic deformation along the Colorado Mineral Belt Shear Zone System. Major structural and metamorphic discontinuities have not been identified across the mylonite zones, S2 high-strain domains, or S1 domains. The Homestake, Gore Range, and Idaho Springs-Ralston shear zones separate plutons from metasedimentary rocks. The Homestake and Gore Range shear zones may have facilitated Paleoproterozoic pluton emplacement, while the Idaho Springs-Ralston shear zone appears to have developed after Paleoproterozoic plutonism and quartzite deposition.

Along the St. Louis Lake shear zone, the rock types within the melange are similar to the rock types in melanges identified within continent-arc collision zones [Chang et al., 2000; Polat and Kerrich, 1999]. The presence of this possible fragment of oceanic melange, surrounded by granites and micaschists, suggests that the shear zone might have an ancestry as a lithospheric-scale structure that facilitated transport and tectonic juxtaposition of far-travelled rocks. The St. Louis Lake melange is similar to that described along the Moose Mountain shear zone in the northern Front Range [Selverstone et al., 2000]. Both shear zones appear to have juxtaposed rocks from different structural levels during D2 and D3 (1.4 Ga) intracontinental deepening of the initially low-angle, continental assembly-related S1 fabrics.

The Paleoproterozoic structures, with inferred deformation dates from 1.7 to 1.62 Ga, developed during a time of regional tectonism that was likely associated with the collision of island arcs, and the welding of packages of arcs to the Archean Wyoming craton [Figure 6a]. Syn-tectonic plutons and batholiths of this period, such as the Cross Creek and Boulder Creek batholiths, do not appear to represent components of the initial magmatic arcs because they do not have isotopic signatures characteristic of arc plutons, and there is no evidence of andesites or adjacent suture zones [Shaw and Karlstrom, 1999; Aleinikoff et al., 1993; Reed et al., 1987].

4.3.2. Tectonic significance of Mesoproterozoic intracontinental deformation along the Colorado Mineral Belt Shear Zone System. In contrast to the D1 and D2 crustal assembly-related deformation that affected broad regions of Colorado, the Mesoproterozoic Colorado Mineral Belt shear zone system formed as a relatively narrow zone at a time when plate convergence was probably occurring some
1,000 km to the south, based on the proposed boundary between the Mazatzal Province and the Grenville Province near the present-day New Mexico/Texas border [Karlstrom and Humphreys, 1998]. At a great distance from this margin, the Mesoproterozoic mylonite system seems to have reactivated a zone of weakness related to Paleoproterozoic assembly. However, Mesoproterozoic mylonitization led to the development of a more focused belt of weakness and defined the trend that has influenced Phanerozoic deformation and magmatism along the Colorado Mineral Belt.

Intracontinental zones of deformation, located well away from plate margins, may be the loci of deformation that accommodate an important part of the observed plate convergence at the margin [Tien Shan of central Asia, Atlas Mountains of northern Africa; Burov and Molnar, 1998, Yin et al., 1998], and may also record lithosphere/asthenosphere interactions. Intracontinental shortening in the Atlas Mountains has accommodated 17–45 percent of the total African-Eurasian plate convergence since the early Miocene [Gomez et al., 2000; Brede et al., 1992]. Late Cenozoic intracontinental shortening in the Tien Shan appears to have resulted in 20 to 40 km of shortening [Yin et al., 1998].

The behavior of intracontinental zones of deformation at depth and over significant time intervals, and the processes controlling these zones, remain poorly understood. Intracontinental zones of deformation may have become weak due to anomalous heat, due to a pre-history that imparted compositional differences between the weak zone and the surrounding lithosphere, due to unusually thick crust, and/or due to the presence of major pre-existing mechanical weaknesses or domains of grain size reduction and strain-softening [Burov and Molnar, 1998; Karlstrom and Humphreys, 1998]. Karlstrom and Humphreys [1998] proposed that inheritance of Proterozoic structural grains throughout the southwest U.S. involves combinations of ‘volumetric’ inheritance (related to the density and fertility of compositionally different lithospheric blocks that influences isostatic and magmatic responses to tectonism) and ‘interface’ inheritance (related to mechanical boundaries that are zones of weakness and mass transport).

The Mesoproterozoic mylonites of the Colorado Mineral Belt shear zone system, as well as the Paleoproterozoic S2 high-strain domains they overprint, record primarily dip-slip movements on subvertical fault planes. The zones appear to have become subvertical during D2, with discrete mylonites reactivating broader S2 domains at middle crustal levels. Given these geometries, the shear zones appear to have caused large-scale ‘jostling’ of blocks [Figure 6a, Figure 6b]. These types of movements could occur along a flower structure or as part of a transpressive system, but we do not find extensive evidence for either horizontal stretching lineations or horizontal shear sense indicators of strike-slip movement.

Comparison of the Colorado Mineral Belt shear zone system with younger analogues can shed light on the importance of intracontinental zones of deformation and the similarities among these zones, and can link the surface and shallow crustal level expression of such zones to their middle crustal analogues. One Cenozoic analogue is the Tien Shan of central Asia, where reactivation has taken place primarily along moderately- to steeply-dipping reverse structures [Avouac et al., 1993; Brookfield, 2000]. Like the Colorado Mineral Belt shear zone system, the Tien Shan region records a complex tectonic history of continental assembly that occurred within a broad, diffuse zone containing slices of many different rock packages [Allen and Vincent, 1997]. In both areas, broad zones of assembly-related foliations were reactivated as narrower, more discrete zones of intracontinental deformation thousands of kilometers from the plate margin. Structures within the Tien Shan and the Colorado Mineral Belt shear zone system are adjacent to plutons, and there is evidence for early syn-plutonic deformation [Figure 7a, Figure 7b; Brookfield, 2000]. Although the magnitude of Precambrian offset across the Colorado Mineral Belt shear zone segments is difficult to determine, the Tien Shan faults have experienced several kilometers of offset during Cenozoic intracontinental reactivation [Yin et al., 1998]. Most earthquakes on the Tien Shan faults have thrust solutions, indicating that this intracontinental zone of deformation is facilitating crustal shortening [Yin et al., 1998].

The North Tien Shan fault is interpreted to have originated as a steeply-dipping ‘back-stop’ to a zone of lithospheric fragments assembled in the late Paleozoic [Allen and Vincent, 1997]. The fault was reactivated in the Cenozoic as a steeply dipping, north-directed thrust following the Paleozoic structural grain, but there is some evidence for dextral strike-slip movement [Allen and Vincent, 1997].

5. CONCLUSIONS

The Colorado Mineral Belt shear zone system is here defined as a Mesoproterozoic system of mylonites and ultramylonites that moved during a protracted period of orogenesis between 1.45 and 1.3 Ga. Although the shear zone system is Mesoproterozoic, the system overprints a broader, higher temperature, high-strain domain that records a >70 Ma Paleoproterozoic orogenic episode. Thus, the Colorado Mineral Belt shear zone system may have reactivated a more diffuse zone of weakness associated with continental assembly, and in doing so, it established the trend that controlled Phanerozoic deformation and localization of magmatic systems along the Colorado Mineral Belt.

The long history of deformation along the Colorado Mineral Belt shear zone system indicates that lithospheric zones
of weakness, first established as diffuse zones of weakness during continental assembly and later reactivated as narrow intracontinental zones, may remain as loci of geologic processes for hundreds of millions of years. This study of the Colorado Mineral Belt shear zone system documents many characteristics of intracontinental tectonic zones including: 1. Origination of such zones in broad, subvertical domains of high strain and foliation intensification that have steepened what are inferred to be initially low angle sheet-like structures; 2. Reactivation of such zones as progressively narrower domains of increasingly higher strain-rate/lower-temperature grain size reduction at progressively shallower depths and lower temperatures, 3. Repeated emplacement of plutons and mineralization along the zones, and 4. Development of lithospheric-scale inhomogeneities such as negative gravity anomalies and slow mantle anomalies associated with the zone.

The Colorado Mineral Belt shear zone system is dominated by steeply-dipping structures with steeply-plunging mineral stretching lineations, indicating primarily dip-slip movements along subvertical zones. A kinematic model that accounts for these movements involves the ‘jostling’ of blocks, up and then down along the same zone of weakness, possibly facilitating pluton emplacement or an interplay between crustal shortening and crustal collapse. Such movements are observed in other intracontinental zones of deformation, such as the Tien Shan of central Asia, the Atlas Mountains of northern Africa, and the Laramide Rocky Mountains. Therefore, dip-slip movement along subvertical zones may be an important characteristic of long-lived intracontinental zones of deformation that have remained as weak zones in the lithosphere, experiencing multiple episodes of reactivation.

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