Characteristics and implications of ca. 1.4 Ga deformation across a Proterozoic mid-crustal section, Wet Mountains, Colorado, USA

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ABSTRACT

In the Wet Mountains, Colorado, Proterozoic rocks exposed along an oblique north-south tilted section preserve evidence of regional deformation and high temperature metamorphism in the middle and lower crust at ca. 1435–1365 Ma. Deformation of gneisses in the northern Wet Mountains is partitioned within discrete zones of subvertical foliation and northeast-trending folds, a product of northwest-southeast contraction or constriction associated with transient deformation. Gneisses in the north are generally not migmatitic, and granitic intrusions form discrete bodies with distinct contacts. Shear zone foliation is cut by a late syntectonic dike with a U-Pb zircon age of 1430±5/–3 Ma, constraining the age of shear zone deformation in the upper crust. In the central to southern Wet Mountains, gneisses exhibit migmatitic foliation that dips moderately northeast, with dip- to oblique-slip mineral lineation throughout. Granite forms pervasive sills and interconnected sheets with gradational or indistinct contacts. Gneissic granite that yields a U-Pb zircon age of 1435 ± 4 Ma was emplaced into amphibolite gneiss containing 1436 ± 2 Ma metamorphic zircon. Younger, foliated granite sills were emplaced at 1390 ± 10 Ma. Our new results indicate contemporaneous deformation and metamorphism throughout the middle and lower crust at ca. 1.4 Ga. We interpret the zone of migmatitic crust pervaded by granite to represent a weak, low-viscosity, flowing lower crust that controlled the pattern of distributed deformation in the comparatively strong, brittle crust above. Thus, the Wet Mountains may be viewed as a deeply exhumed analog for the mid-crustal, low-viscosity layers that are inferred to exist in modern intracontinental orogenic settings and continental rift provinces.

INTRODUCTION

The regional context and tectonic setting for widespread Mesoproterozoic (ca. 1.4 Ga) granitic magmatism across the southwestern United States has long been a subject of debate. Granites of this age were formed during an interval of voluminous igneous activity between 1.6 and 1.3 Ga that occurred throughout Paleoproterozoic crustal provinces in Laurentia and Baltica, and granites of similar age have been documented on nearly every other continent (Anderson and Morrison, 2005). Petrogenetic models constrained by geochemical and isotopic data (e.g., Anderson and Cullers, 1999; Frost et al., 2001b; Goode and Vervoort, 2006) typically involve widespread partial melting of preexisting Paleoproterozoic lower crust of varying compositions (Anderson and Morrison, 2005). In North America the alkaline, ferroan geochemistry of the granites (A-type, sensu lato; Frost et al., 2001a) and a perceived lack of dynamic fabric throughout the plutons and batholiths (Bickford and Anderson, 1993) are viewed as evidence for regional plutonism within a setting of crustal extension or mantle upwelling (Anderson, 1983; Hoffman, 1989; Frost and Frost, 1997; Ferguson et al., 2004). Consistent with this model, the evidence for high-temperature, low-pressure metamorphism at ca. 1.4 Ga is widespread (Pedrick et al., 1998; Williams et al., 1999). The thermal perturbation caused resetting of 40Ar/39Ar ages in Paleoproterozoic rocks exposed throughout the southwestern United States, with temperatures >550 °C attained in the vicinity of the Wet Mountains of southern Colorado (Fig. 1; Shaw et al., 1999, 2005).

Throughout the subsurface of the mid-continent region, the voluminous ferroan granites emplaced at shallow levels at ca. 1.4 Ga are largely undeformed (Bickford and Anderson, 1993). However, in exposures of the Rocky Mountains and the southwestern United States (Fig. 1), ca. 1.4 Ga granites commonly exhibit foliation (e.g., Aleinikoff et al., 1993) and, in many cases, are spatially associated with lithosphere-scale shear zones (e.g., Selverstone et al., 2000; Shaw et al., 2001; Jessup et al., 2006). Regional shear zones and other coeval deformational features generally record northwest-southeast shortening that has been attributed to intracontinental tectonism at ca. 1.4 Ga driven by active convergence along the distal southern margin of Laurentia (Nyman et al., 1994). The finding of contractional deformation that is contemporaneous with ferroan, alkaline magmatism presents a serious problem from a petrological standpoint, however, because such granites are nearly universally derived from magmatic differentiation of mantle-derived tholeiite and are associated with extensional or hotspot settings (Frost et al., 2001a).

The Wet Mountains are a critical locality in which to examine the discrepancy between petrological models and structural observations for events at ca. 1.4 Ga. Proterozoic gneiss exposed throughout the Wet Mountains host voluminous alkaline, ferroan granites (Bickford and Anderson, 1993; Cullers et al., 1992; Cullers et al., 1993) and exhibit structures formed during northwest-southeast shortening (Siddoway et al., 2000) or east-northeast–west-southwest dextral transtensive deformation (Andrénicos et al., 2002). Non-migmatitic mid-crustal gneisses in the north pass into migmatitic gneisses that represent deeper levels in the south (Figs. 1 and 2), a transition that is accompanied by a change in structural style and a mode of plutonism from discrete plutons to pervasive dikes and...
sills (Bickford et al., 1989). In this paper we present new high-precision U-Pb geochronology for zircon and titanite in order to refine the ages of magmatism, deformation, and metamorphism during the ca. 1.4 Ga event in the northern and southern Wet Mountains. We sampled granites, granite gneisses, and amphibolite gneisses from exposures across the contrasting structural levels to determine the age of shear zone development in the north versus penetrative deformation in the south. The new data help to refine our understanding of the contradictory viewpoints on the question of Mesoproterozoic granite emplacement in a contractional (Nyman et al., 1994) versus an extensional setting (e.g., Anderson, 1983; Anderson and Cullers, 1999; Frost et al., 2001b; Selverstone et al., 2000). Our aim is to provide a sound geochronological framework for the ongoing effort to develop a tectonic model that unifies petrological, geochemical, and structural geology data for the 1.4 Ga event in the Wet Mountains, with consequences for the broader region of southwestern Laurentia.

GEOLOGIC SETTING

Exposures of Precambrian crustal rocks across the southwestern United States are made up of a diverse assemblage of metavolcanic rocks, metasedimentary rocks, and mafic and granitoid plutons that were formed and accreted to the southern margin of the Archean Wyoming Province between 1.8 and 1.6 Ga (Condie, 1982; Karlstrom and Bowring, 1988; Reed et al., 1993) as part of a protracted period of Laurentian crustal growth (Whitmeyer and Karlstrom, 2007). These exposures have been divided into several orogenic provinces on the basis of rock ages and isotopic characteristics (Fig. 1). The Yavapai Province is interpreted to represent a complex collage of predominantly juvenile arc terranes characterized by rocks with Nd model ages between 2.0 and 1.8 Ga (Bennett and DePaolo, 1987) and accreted to southern Laurentia margin 1.78–1.70 Ga along a belt stretching from Colorado to Arizona and New Mexico (Fig. 1). The final collisional phase of this long-lived, progressive orogenic event occurred between ca. 1.71 and 1.70 Ga (Karlstrom and Bowring, 1988) and was followed by ~40 m.y. of voluminous post-orogenic granitoid magmatism (Anderson and Cullers, 1999), erosional unroofing, and widespread sedimentation (Jones et al., 2009). The Mazatzal Province lies to the south of the Yavapai Province and extends across central and southern New Mexico and Arizona (Fig. 1). Mazatzal Province rocks are characterized by Nd model ages between 1.8 and 1.7 Ga (Bennett and DePaolo, 1987) and were accreted to southern...
Figure 2. Generalized Precambrian geology of the Wet Mountains, Colorado. Areas sampled for new U-Pb geochronology and summary of new U-Pb zircon ages are indicated, along with a summary of published U-Pb ages.
Laurentia during the Mazatzal orogeny ca. 1.66–1.60 Ga (Silver, 1965; Karlstrom and Bowring, 1988; Amato et al., 2008). Deformation related to the Mazatzal orogeny propagated northward into the southwestern part of the Yavapai Province (Transition Zone, Fig. 1), and the Mazatzal deformation front represents the approximate northern limit of these effects (Shaw and Karlstrom, 1999). Various workers have challenged the juvenile arc accretion model for the Yavapai and Mazatzal orogenies on the basis of zircon ages, lithological associations, and limited Hf isotopic data (Bickford and Hill, 2007a; Bickford et al., 2008), but alternative models are still being evaluated and debated (Duebendorfer, 2007; Karlstrom et al., 2007; Bickford and Hill, 2007b).

After an ~150 m.y. tectonic lull, renewed southward growth of Laurentia is inferred to have occurred during the Mesoproterozoic. This interpretation is based on a large crustal province with Nd model ages of 1.5–1.3 Ga extending from northern Mexico to Labrador, Canada (Bennett and DePaolo, 1987; Patchett and Ruiz, 1989; Karlstrom et al., 2001). An episode of widespread granitic magmatism, local emplacement of mafic dikes, and regional high-temperature, low-pressure metamorphism occurred throughout the southwestern United States between 1.47 and 1.36 Ga (Reed et al., 1993; Williams, 1991; Williams et al., 1999), and rocks of this age currently account for nearly 20% of all Precambrian exposures in the region (Fig. 1). Circa 1.4 Ga granites, previously described as being A-type because of their alkalinity, anhydrous character, and presumed anorogenic tectonic setting (Loiselle and Wones, 1979; Anderson, 1983; Anderson and Cullers, 1999), are ferroan in nature (Frost et al., 2001a), a geochemical characteristic that is indicative of mantle influence (Frost and Frost, 1997) and is generally associated with extensive tectonic environments such as continental rifting (Emslie, 1978; Whalen et al., 1987; Eby, 1990). However, regional evidence exists for contractional to strike-slip deformation within the thermal aureoles of plutons and contemporaneous reactivation of northeast-striking crustal shear zones in the Rocky Mountains and southwestern United States (Graubard and Mattinson, 1990; Shaw et al., 2001; McCoy et al., 2005; Jessup et al., 2006). Nyman et al. (1994) suggested that ca. 1.4 Ga magmatism coincided with regional contraction arising from a convergent plate boundary on a distal southern margin of Laurentia.

PROTEROZOIC GEOLOGY OF THE WET MOUNTAINS

The Wet Mountains, Colorado, lie within the Yavapai Province south of the Mazatzal deformation front (Fig. 1; Shaw and Karlstrom, 1999) and constitute a large (100 km × 30 km) block of nearly continuous Proterozoic exposure that is transected by Phanerozoic brittle faults (Fig. 2). Over the Wet Mountains, aeromagnetic anomaly patterns (Oshetski and Kucks, 2000) define strong northeast-trending lineaments that may correspond with structures that were developed during Paleoproterozoic accretion (Karlstrom and Bowring, 1988; Karlstrom and Humphreys, 1998). Circa 1.4 Ga plutons in the Wet Mountains are spatially associated with the lineaments, suggesting that they may have been reactivated during the Mesoproterozoic (Finn and Sims, 2005). Together with the magnetic data, a pronounced positive gravity anomaly for the Wet Mountains (Snelson et al., 2005; Pardo et al., 2008) suggests the presence of abundant Fe-enriched plutonic rocks beyond the limits of current exposures.

Metavolcanic and metasedimentary successions dominated by quartzose and quartzfeldspathic gneisses make up most of the basement exposures in the northern Wet Mountains. The basement rock assemblage also includes abundant schist, calc-silicate gneiss, mafic gneiss, and amphibolite (Fig. 3). Map-scale lithologic units range in thickness from tens to hundreds of meters, and contacts are commonly sharp but are locally gradational across distances of a few meters. Superb exposures are accessed along the approximately east-west Arkansas River canyon in the northern part of the range (Arkansas River Gorge; Fig. 3). Basement exposures throughout the central and southern Wet Mountains have a narrower compositional range and are dominated by interleaved quartzose and quartzofeldspathic gneisses, amphibolite gneisses, and metagabbro (Fig. 4). Rare exposures of schist, marble, and calc-silicate gneiss exist. In general, metamorphic grade increases from north to south across the range. Whereas exposures in the Arkansas River Gorge record peak metamorphic conditions of greenschist to amphibolite facies (Siddoway et al., 2000), gneisses of the central and southern Wet Mountains are migmatitic throughout (e.g., Boyer, 1962; Siddoway et al., 2000) and underwent upper-amphibolite- to granulite-facies metamorphism (Brock and Singewald, 1968; Lanzinotti, 1988). Amphibole is stable throughout the central and southern Wet Mountains, and 40Ar/39Ar hornblende thermochronologic data indicate temperatures exceeding 500 °C over a wide region in the southwestern part of the range at ca. 1.4 Ga, compared with temperatures of 350–500 °C in the north during the same time (Fig. 1; Shaw et al., 2005; Siddoway et al., 2000).

Numerous granitoid intrusions cut across the basement rock assemblages in the Wet Mountains, and these igneous rocks are divided into two general age groups. Paleoproterozoic intrusive rocks are correlated with the Routt plutonic suite of Tweto (1987) and include foliated tonalite and granodiorite of the ca. 1705 Ma Twin Mountain and Crampton Mountain plutons and weakly foliated to undeformed granodiorite of the ca. 1663 Ma Gare Peak pluton (Fig. 3; Bickford et al., 1989). Other Paleoproterozoic intrusive rocks, broadly referred to as G1 granitoids by Siddoway et al. (2000), are exposed as networks of coarse-grained to K-feldspar-megacrystic dikes and sills that are isoclinally folded and share the host rock foliation but have margins that are obliquely discordant to compositional layering in wall rocks. Mesoproterozoic intrusive rocks are correlated with the Berthoud suite of Tweto (1987) and contain a variably deformed suite of Mesoproterozoic granites emplaced between 1474 and 1361 Ma (Bickford et al., 1989). In the northern Wet Mountains, Mesoproterozoic intrusions include the relatively undeformed West McCoy Gulch and Hindman Gulch plutons and strongly foliated Oak Creek pluton (Figs. 2 and 3; Bickford et al., 1989; Cullers et al., 1993). In the central and southern Wet Mountains, Siddoway et al. (2000) described two separate suites of presumed Mesoproterozoic granitoids that are primarily exposed as networks of sills and dikes. Coarse-grained to K-feldspar megacrystic granites referred to as G2 by Siddoway et al. (2000) are commonly concordant with respect to wall-rock gneiss foliation and are locally strongly deformed. A younger suite of granitoids referred to as G3 (Siddoway et al., 2000) contains fine-grained granitic sills that are concordant to discordant with respect to wall-rock gneiss foliation but commonly contain a well-developed dynamic foliation that is parallel with the surrounding wall-rock and granite fabric. The youngest Mesoproterozoic intrusion in the entire range is the San Isabel pluton (Fig. 2), an extensive body ~10 km by 30 km as exposed in the southern Wet Mountains. The San Isabel pluton consists of largely undeformed monzogranite to syenogranite that crystallized 1371–1362 Ma (Bickford et al., 1989) at depths estimated at 17–23 km (500–700 MPa) on the basis of Al-in-hornblende geobarometry and the presence of primary, euhedral magmatic epidote (Cullers et al., 1992). Abundant sapphire is stable in large roof pendants within the San Isabel batholith (Heimann et al., 2005), an indication that gneisses of the southern Wet Mountains attained temperatures ≥700 °C (Raymond et al., 1980) during its emplacement.

In the northern Wet Mountains, granitoids such as the West McCoy Gulch pluton (Fig. 2) are commonly exposed as discrete, map-scale bodies with sharp contacts. Although similar map-scale intrusions with distinct contacts such as the Oak Creek and San Isabel plutons also occur in exposures farther to the south (Fig. 2), the prevalent form of granite...
Figure 3. Generalized geologic map of the eastern Arkansas River Gorge, northern Wet Mountains, Colorado. See index for sources of geologic mapping and structural data. New U-Pb ages (this study) and published ages of the Crampton Mountain batholith (Bickford et al., 1989) are indicated. Structural data and synthesis from the Five Points Gulch shear zone (FPSZ) and Sheep Basin domain are represented on lower-hemisphere, equal-area stereonet diagrams. Foliation plotted as poles, and lineation data are plotted separately, with the rock type from which measurements were taken indicated above the diagrams. Average orientations were calculated using GEOrient 9.1 (Holcombe, 2003).
Figure 4. Generalized geologic map of Precambrian exposures in the southern Wet Mountains (redrafted, simplified, and reinterpreted from Boyer, 1962). Structural data for basement gneiss and granites (G2 and G3) are represented on lower-hemisphere, equal-area stereonet diagrams. Foliation (plotted as poles) and lineation data are plotted separately, with the rock type from which measurements were taken indicated above the diagrams. Average orientations were calculated using GEOrient 9.1 (Holcombe, 2003).
occurs as a network of G2 and G3 granitoid sills and dikes that pervade the gneissic host rock. Igneous bodies, meters to centimeters in dimension, form a distributed magmatic framework that makes up 40% to 100% of outcrops. Owing to the pervasive nature and indistinct contacts of the diverse granites, many of which exhibit penetrative dynamic fabrics, most of the Wet Mountains have been represented on geological maps as undifferentiated Proterozoic gneisses (e.g., Scott et al., 1978) with relatively few map-scale intrusive bodies. Notable exceptions are the detailed map of Brock and Singewald (1968) and the moderately detailed map of Boyer (1962), both of which attempted to distinguish the diverse granites and granitic gneisses that constitute the Mesoproterozoic bedrock. The location and nature of the transitional boundary between the discrete plutons within nonmigmatitic gneisses in the north to the region of diffuse “framework” magmatism within migmatites in the south coincide with a kilometer-wide zone of voluminous granite and pegmatite south of the Arkansas River Gorge (Siddoway et al., 2000) of presumed ca. 1.4 Ga age.

Proterozoic Structural Elements

The change in the style of magmatism from north to south across the range coincides with a change in structural style and fabric orientation. The northern part of the range exhibits upright, open folds and subvertical foliation formed at moderate metamorphic conditions, whereas the central and southern part of the range contains shallowly to moderately dipping, penetrative gneissic fabrics formed at high temperatures. In our research we selected two areas in the north and south to map in detail, with attention to deformation structures, fabric and fold orientations, and kinematics. The mapping guided the selection of samples for new U-Pb geochronology described below.

Figure 3 is a compilation map for Proterozoic exposures along the Arkansas River Gorge in the northern Wet Mountains. The central element is the 2–5-km-wide Five Points Gulch shear zone (Fig. 3; Siddoway et al., 2000), a north-northwest-striking, subvertical high strain zone that exhibits an oblique lineation defined by aligned sillimanite. Exposures within the shear zone are dominated by K-feldspar-biotite-quartz-plagioclase-muscovite gneisses with localized zones of quartz-muscovite ± sillimanite “pod” rock (e.g., Pedrick et al., 1998). High-strain layers separate lower strain domains with biotite foliation that is tightly folded into upright, north-northwest–trending folds. The dominant shear zone fabric (S1) strikes north-northwest and dips steeply east-northeast, with an average orientation of 335/63°E (Fig. 3A). The sillimanite mineral lineation plunges moderately north-northeast with an average orientation of 45°/015 (Fig. 3B) but is locally steep to subvertical. The presence of strongly aligned prismatic sillimanite and garnet with symmetrical tails within high strain zones indicates peak metamorphic conditions of >700 °C and 500 MPa during shear zone deformation (Givot and Siddoway, 1998). Kinematic indicators across the shear zone include ductile shear bands, asymmetric tails on garnet, and en echelon tension-gash arrays. Many of these indicators appear in zones with minor amounts of leucosome, suggesting onset of melting (cf. Sawyer, 2008) during one episode of movement along the shear zone. Kinematic indicators and asymmetric folds in parts of the shear zone with steeply plunging lineations show sinistral reverse-oblique, east-side-up displacement (Fig. 5), consistent with the juxtaposition of higher temperature shear zone rocks against the lower temperature Texas Creek association to the west (Siddoway et al., 2000).

We identify two domains with contrasting fabric geometries, deformation styles, and/or fabric intensity on either side of the Five Points Gulch shear zone; these are the Texas Creek and Sheep Basin domains to the west and east, respectively (Fig. 3). Quartzose and quartzofeldspathic gneisses of sedimentary origin dominate exposures in the Texas Creek domain (Fig. 3), and these rocks are interfolded and interfoliated with a mafic and felsic association of gneisses (Siddoway et al., 2000) that originated as bimodal volcanic rocks (Stiles, 1997; Wearn and Wobus, 1998). Subordinate schists contain mineral assemblages indicative of metamorphism at 650 °C and <400 MPa (Siddoway et al., 2000; Goodge and Siddoway, 1997). Large cordierite poikiloblasts within one schist unit preserve a penetrative crenulation cleavage (S1) that disrupts compositional layering defined by quartz and opake inclusions, inferred to be relic bedding (Siddoway et al., 2000). Microstructural relationships indicate S1 development during an early stage of a progressive deformation event (D1) accompanied by metamorphism (M1) involving growth of 10–20 cm cordierite and plagioclase poikiloblasts (Siddoway et al., 2000). Outside the metamorphic megacrysts, the dominant foliation, S2, is defined by aligned micas and quartz ribbons, and S2 wraps around the cordierite poikiloblasts. S2 forms the dominant fabric and compositional layering in the Texas Creek association as a whole. The S2 fabric is deformed by upright,
kilometer-scale, east-trending folds (F2) with a cumulative \( \pi \)-axis orientation of 45°/081 (Siddoway et al., 2000). These folds are interpreted to have formed during a second deformation event (D2) involving subhorizontal, north-northwest-directed shortening (Siddoway et al., 2000), and they are sharply truncated to the east by the Five Points Gulch shear zone.

East of the Five Points Gulch shear zone, along the easternmost 10 km of the Arkansas River Gorge, exposures in the Sheep Basin domain consist of tonalite, quartz diorite, and granodiorite of the 1705 ± 8 Ma Crampton Mountain pluton (Bickford et al., 1989) along with localized exposures of gray quartz biotite and amphibolite gneiss wall rock. On the western side of the domain the north-northwest–striking fabric of the Five Points Gulch shear zone passes into asymmetric northeast-plunging folds in the gneisses over a distance of a few hundred meters. Northeast-striking, subvertical foliation in gray gneisses has an average orientation of 235/87° NW (Fig. 3C) and is defined by biotite and amphibole and locally enhanced by dynamically recrystallized plagioclase, K-feldspar, and quartz. The foliation orientation is generally parallel to the western margin of the 150 km² Crampton Mountain pluton (Fig. 3), and abundant flattened mafic enclaves with aspect ratios up to 30:1 are parallel with the surrounding fabric (Fig. 5C).

Well-developed biotite and/or amphibole mineral lineation in the metapelite rocks plunges moderately to steeply northeast with an average orientation of 62°/045 (Fig. 3D). Locally developed asymmetric fabrics include C-S foliation and ductile shear bands (Fig. 5C). Kinematic indicators observed along the east-northeast–trending southern margin of the Crampton Mountain pluton (Fig. 3 map) show dominantly reverse, northwest-side-up displacement with a component of sinistral offset. The eastern boundary of the Sheep Basin domain is the Ise fault zone, a structure of probable Neoproterozoic ancestry (cf. Timmons et al., 2002) that most recently was reactivated during formation of the Tertiary Parkdale graben (Fig. 3; Fryer, 1996; Kelley and Chapin, 2004).

In exposures ~15 km south of the Arkansas River Gorge, focused work on the Mesoproterozoic Oak Creek pluton (Dean et al., 2002) established that the intrusion has a layered character indicative of emplacement in sheets and exhibits a northwest-striking solid-state foliation concordant with that in host gneisses. An east-southeast–trending mineral-stretching lineation is well developed, particularly on the pluton margins, and is associated with kinematic criteria that indicate normal-oblique displacement with pluton side down.

Exposures in the central and southern Wet Mountains exhibit remarkably consistent geometries of foliation and folds that define a dominant east-west pattern over 100 km² of exposure (Fig. 4). Deformation affected both wall-rock gneisses and granitic phases G1 through G3 that pervade the range, as is evident where foliation trajectories cross multiple lithologic boundaries in Figure 4. The dominant compositional layering and migmatic foliation in the central Wet Mountains strikes east-west with moderate to shallow north-northwest dips with an average orientation of 270/50°N (Siddoway et al., 2000; Jones, 2005). North-plunging biotite lineation with an average orientation of 52°/003 is well developed in biotite gneiss units and at granitic gneiss–amphibolite gneiss contacts (Siddoway et al., 2000; Jones, 2005). Tight-to-isoclinal folds with amplitudes ranging from tens of centimeters to more than a kilometer deform the gneissic layering and granitic sills, providing evidence that the foliation is a composite fabric that resulted from multiple episodes of broadly coaxial deformation. In the southern Wet Mountains there is some discrepancy in the foliation orientations of G2 and G3 granite intrusions versus those of the gneissic rocks. Whereas the average foliation in gneisses strikes east-west and dips moderately north (average orientation, 283/56°N; Fig. 4), consistent with the central domain, the well-developed, locally gneissic foliation in G2 and G3 sills strikes east-northeast and dips moderately north-northwest (average orientation, 243/43°N; Fig. 4C). Mineral lineation in both gneisses and G2 + G3 granites is essentially parallel, trending toward azimuth 350–355 (Fig. 4B and 4D). Kinematic shear sense indicators, including asymmetric folds, indicate reverse (top to the south) shear sense in both wall-rock gneisses and G2 and G3 granite sills.

In the central Wet Mountains, Lanzirotti (1988) found evidence for three episodes of penetrative deformation, all attributed to northwest–southeast shortening, in exposures in the Tyndall Mountain quadrangle (Brock and Singewald, 1968). The first two deformation events (D1 and D2) are broadly correlated with ca. 1.7 Ga plutonism, constrained locally by a 1692 ± 5 Ma U-Pb zircon age (Bickford et al., 1989) from granulites in the central part of the range (Lanzirotti, 1988; Brock and Singewald, 1968). Lanzirotti (1988) suggested that the third deformation (D3) might have coincided with the emplacement of a suite of younger deformed plutons at 1650–1615 Ma (Bickford et al., 1989), but D3 might have been contemporaneous also with ca. 1.4 Ga metamorphism and magmatism. U-Pb zircon and titanite data from 10 km to the east along Rattlesnake Gulch (Fig. 2) suggest that 1691–1680 Ma amphibolite and felsic gneiss underwent at least one episode of deformation involving foliation development and isoclinal folding prior to emplacement of a fine-grained granite sill 1679 ± 2 Ma (Jones, 2005). There is also evidence of metamorphic zircon and titanite growth or recrystallization in amphibolite between 1436 and 1390 Ma accompanied by at least one episode of deformation involving fabric overprinting or reactivation (Jones, 2005). However, direct evidence of ca. 1.4 Ga magmatism is lacking from the central Wet Mountains.

U-Pb GEOCHRONOLOGY

We undertook new U-Pb geochronology to constrain precisely the age of deformation and metamorphism in the northern and southern Wet Mountains, respectively. Samples were collected from the well-characterized structural sites described in the previous section to help assess whether the contrasting structural styles developed in the northern versus the central and southern part of the range were contemporaneous or had developed at different times. Because the age of deformation in the Texas Creek domain of the Arkansas River Gorge was reasonably well established (see below; Siddoway et al., 2002; Siddoway et al., 2000), sampling in the northern Wet Mountains was concentrated within the Five Points Gulch shear zone and Sheep Basin domain to address the timing of deformation in the shear zone and in metapelite rocks exposed in the eastern Arkansas River Gorge (Fig. 3). In the southern Wet Mountains, we targeted multiple generations of deformed tabular granite intrusions that occur as a network of sills and sheets in outcrop and their metamorphosed Paleoproterozoic country rocks. The samples were collected from a single large exposure of gneiss and granite along the Wet Mountains’ southwestern escarpment near the intersection of Bear Creek and Williams Creek (Boyer, 1962; Callahan, 2002; Perkins, 2002). This exposure, informally named “The Wall” because of its subvertical aspect, nearly 100 m in height (Fig. 6), is 0.5 km east of the Pole Creek Trailhead along San Isabel National Forest Road 630 (Fig. 4).

Sample processing and analytical techniques followed those described by Jones and Connelly (2006). We present isotopic data and sample location coordinates in Table 1 and associated concordia diagrams in Figures 7 and 8. Results described in the following section are grouped according to general locations in the Wet Mountains.

Northern Wet Mountains–Arkansas River Gorge

**Deformed Pegmatite Dike (J01-FP1)**

Within the Five Points Gulch shear zone there is an array of subvertical dikes oriented parallel to the north-northwest–striking shear zone...
Figure 6. Field photograph of "The Wall," a large, vertical exposure in the southern Wet Mountains that is characterized by penetrative, moderately north-northwest-dipping fabrics. Sample localities for U-Pb geochronology (see Fig. 9) are indicated by stars.

**Table 1. Wet Mountains U-Pb Isotopic Data**

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<th>Measured</th>
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<td></td>
<td>U (ppm)</td>
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<td>Common Pb&lt;sup&gt;T&lt;/sup&gt;</td>
<td>206&lt;sup&gt;Pb&lt;/sup&gt;/238&lt;sup&gt;U&lt;/sup&gt;</td>
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<td>Deformed pegmatite dike (J01-FP1; N 38° 27’32”, W 105° 30’33.3”)</td>
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<td>919</td>
<td>139</td>
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<tr>
<td>Foliated quartz diorite, Crampton Mountain pluton (J03-TM1; N 38° 28’79”, W 105° 25’36”)</td>
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<td>168</td>
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<tr>
<td>T2</td>
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<td>10.6</td>
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<tr>
<td>T3</td>
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<td>919</td>
<td>139</td>
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<tr>
<td>Amphibolite (J01-WC1; N 37° 55’22”, W 105° 9’97”)</td>
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Abbreviations: abr—abraded; ang—angular; bge—beige; brn—brown; clr—clear; dk—dark; euh—euhedral; frags—fragments; lg—large; lt—light; md—medium; orng—orange; prsm—prisms; sm—small; sbrnd—subround.

*Ratios corrected for fractionation; 1 pg and 0.25 pg laboratory Pb and U blanks, respectively, and initial common Pb calculated using Pb isotopic compositions of Stacey and Kramers (1975). All fractions of zircon and titanite are extensively abraded (Krogh, 1982) unless otherwise noted. Two-sigma (2σ) uncertainties on isotopic ratios are reported after the ratios and refer to the final digits. Pb<sup>R</sup> refers to radiogenic Pb; Common Pb<sup>T</sup> refers to total common Pb.
Figure 7. U-Pb concordia diagrams for samples from the Arkansas River Gorge, northern Wet Mountains. Ages are determined by linear regression through the data except where indicated, and probability of fit (%) is indicated in parentheses. See text for details.

Figure 8. U-Pb concordia diagrams for samples from the southern Wet Mountains. Ages are determined by linear regression through the data except where indicated, and probability of fit (%) is indicated in parentheses. See text for details.
DEFORMATION ACROSS A PROTEROZOIC MID-CRUSTAL SECTION

The pegmatite yielded a single population of tan to brown, euhedral to subhedral zircon with prismatic faces indicative of an igneous origin. Most of the grains contain dark brown xenocrystic cores surrounded by light tan to clear euhedral tips (Fig. 7A inset). Tips were mechanically separated from core material using tweezers, and the constituent parts of the grains were then abraded, dissolved, and analyzed separately. The $^{207}\text{Pb}/^{206}\text{Pb}$ ages of two core fractions of dark brown zircon material overlap concordia at 1451 and 1449 Ma (fractions Z1 and Z4, Table 1; Fig. 7A). Three fractions of zircon tip material (Z2, Z3, and Z5) define a line with intercepts of 1430±5–3 Ma and 252 ± 300 Ma (Fig. 7A).

Foliated Quartz Diorite of the Crampton Mountain Pluton (J03-TM1)

Quartz diorite exhibiting C-S foliation was collected from exposures in the Sheep Basin domain for U-Pb titanite geochronology to determine the age of dynamic metamorphism and foliation development. The U-Pb zircon age of 1705 ± 8 Ma for emplacement of the Crampton Mountain pluton was determined previously by Bickford et al. (1989). The sample site is in the southwestern part of the Crampton Mountain pluton ~1 km west of the dated locality of Bickford et al. (1989) (Fig. 3). Titanite observed in thin section forms submillimeter clusters that are elongate parallel to the biotite foliation, indicating that titanite formed as a product of metamorphic recrystallization. Abundant titanite in the mineral separate consists of dark brown angular fragments that were handpicked for three fractions (T1–T3; Table 1). The $^{207}\text{Pb}/^{206}\text{Pb}$ ages range from 1443 to 1404 Ma (Table 1), and fractions T2 and T1 overlap concordia at 1422 Ma and 1404 Ma (Fig. 7B).

Southern Wet Mountains–Bear Creek–Williams Creek

Amphibolite (J01-WC1)

Medium- to coarse-grained amphibolite is the prevalent host rock to the two generations of granite, G2 and G3. This sample contained sparse relict clinopyroxene, nearly wholly replaced by amphibole with pronounced shape preferred orientation. Prominent foliation strikes east-west and dips moderately north, hosting a north-northwest–plunging amphibole lineation (Fig. 4A and 4B). The amphibolite yielded a single population of pink to tan, subrounded to subhedral, equant zircon interpreted to be metamorphic in origin. Three fractions (Z1–Z3) plot close to concordia and have an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1436 ± 2 Ma (Fig. 8A).

Coarse-Grained, Foliated Granite Sill (J01-WC2)

Coarse-grained to K-feldspar-megacrystic G2 granite forms 1–5-m-thick sills in exposures throughout the southern Wet Mountains. The granite margins are generally concordant with host rock foliation but also cut obliquely across compositional layering and isoclinal folds in the gneisses. Moderate to strong foliation in the sills is defined by crystallographic preferred orientation of biotite and dynamically recrystallized K-feldspar and quartz (Fig. 9A). The dynamic fabric strikes east-northeast and dips moderately north-northwest (Fig. 4C), hosting a pronounced downdip foliation (Fig. 3). These intrusions both follow and sharply cut across the shear zone fabric, $S_z$, and they generally lack internal foliation; thus they are interpreted to be coeval with at least one major phase of shear zone deformation. To determine the age of syntectonic dike emplacement, a 20–30-cm-thick, subvertical pegmatitic dike was sampled near the east margin of the Five Points Gulch shear zone (Fig. 3; Table 1). The pegmatite dike is concordant but truncates the shear zone foliation along parts of its margin. It is cut in turn by a series of en echelon, east-dipping shear bands with reverse-oblique kinematics (Figs. 5A and 5B), consistent with east-side-up displacement across the Five Points Gulch shear zone (Sid-doway et al., 2000).

Figure 9. Field photographs of granitoids exposed in the southern Wet Mountains. (A) View down on G2 granite float block with gneissic fabric defined by recrystallized K-feldspar and biotite. (B) View down on G3 fine-grained granite sill cutting obliquely across gneissic foliation (highlighted by lines) in coarse-grained G2 granite. (C) G3 granite sill containing well-developed foliation and small, asymmetric open folds. Folds have southward vergence that is consistent with reverse-sense, top-up-to-the-south–southeast kinematic indicators elsewhere throughout the sill.
mineral lineation defined by biotite and quartz (Fig. 4D). Asymmetric folds and mineral microstructures record reverse-sense, top-up-to-the-south–southeast kinematics.

The G2 granite yielded a single population of pink to clear, euhedral to subhedral, prismatic zircon consistent with an igneous origin. Three fractions (Z1–Z3) overlap concordia with an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1435 ± 4 Ma (Fig. 8B), and this age is interpreted to represent emplacement and crystallization of the coarse-grained granite. The granite also yielded abundant dark brown, angular titanite fragments. Thin section study revealed the presence of titanite oriented parallel to the dominant gneissic fabric defined by dynamically recrystallized K-feldspar, quartz, and biotite, an indication that titanite grew or recrystallized during metamorphism accompanying solid-state deformation of the granite sill. Three titanite fractions (T2, T4, and T5) define a line with intercepts of 1375 ± 2 Ma and 43 ± 65 Ma, and two fractions (T1 and T3) are colinear along a reference chord with intercepts of ca. 1362 Ma and 0 Ma (Fig. 8B).

Fine-Grained, Foliated Granite Sill (J01-WC3)

Fine-grained G3 granite forms sills that cut across foliated G2 granite sills and foliation, with compositional layering and isoclinal folds in both amphibolite gneiss and granitoid gneisses (Fig. 9B). G3 sills range in thickness from 0.5 to 5.0 m and exhibit solid-state biotite foliation that strikes east-northeast and dips moderately north-northwest (Fig. 4C), with moderately north-northwest–plunging biotite mineral lineation (Fig. 4D). Asymmetric mineral fabrics record reverse-sense, top-up-to-the-south–southeast kinematics, and entire sills are locally deformed by asymmetric folds with east-trending axes and southward vergence (Fig. 9C).

The G3 granite yielded a single population of brown to tan, equant, euhedral to subhedral prismatic zircon. We interpret that clear, euhedral tips surrounding slightly darker, translucent xenocrystic cores represent igneous overgrowths. The small size of the zircon grains made mechanical separation of the cores from rims impossible; therefore air abrasion of shorter duration was used so that the volumetrically minor amount of overgrowth material was retained. Four zircon fractions (Z1–Z4) define a line with intercepts of 1749 ± 28 Ma and 1390 ± 10 Ma (Fig. 8C).

**DISCUSSION**

**Interpretation of U-Pb Geochronology Results**

The late tectonic pegmatite dike (J01-FP1) intruded near the eastern margin of the Five Points Gulch shear zone yielded zircon cores with ages of 1451 and 1449 Ma (Fig. 7A) that are interpreted to represent inherited grains derived from nearby Mesoproterozoic granite plutons such as the Oak Creek pluton (Fig. 2). We interpret the upper intercept age of 1430±5/–3 Ma for the zircon tips to represent growth during crystallization of the pegmatite dike, with the lower intercept reflecting more recent Pb loss caused by a disturbance arising from Phanerozoic tectonism. Growth of metamorphic titanite occurred from 1443 to 1404 Ma during development of the northeast-striking foliation within quartz diorite of the Crampton Mountain pluton (J03-TM1, Fig. 7B), which we attribute to the deformation that caused development of northeast-trending asymmetrical folds in the Sheep Basin domain. We interpret the range of ages from the titanite fractions to reflect pulses of metamorphism throughout a protracted Mesoproterozoic tectono-thermal event in the northern Wet Mountains, consistent with $^{40}\text{Ar}/^{39}\text{Ar}$ ages from across the region (Shaw et al., 2005; Siddoway et al., 2000).

Consistent U-Pb zircon ages of ca. 1435 Ma were acquired from samples of granite and amphibolite gneiss from the southern Wet Mountains. The coarse-grained K-feldspar-megacrystic G2 granite (J01-WC2) yielded three concordant zircon fractions with an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1435 ± 4 Ma (Fig. 8B), interpreted to represent the time of emplacement and crystallization of the pervasive granite sills. The 1436 ± 2 Ma age of metamorphic zircon within amphibolite gneiss that forms part of the host rock is identical within analytical uncertainty to the age of associated G2 granite. The amphibolite gneiss contains evidence for extensive retrogression of clinopyroxene to amphibole, an indication that heat and possibly fluids introduced during the voluminous emplacement of G2 sills caused dynamic recrystallization and breakdown of primary pyroxene, leading to growth of metamorphic zircon.

U-Pb results for metamorphic titanite from the G2 granite reveal that tectonothermal metamorphism continued after G2 emplacement at ca. 1435 Ma in the southern Wet Mountains. Two titanite age populations define reference chords with upper intercepts at 1375 ± 2 Ma and ca. 1362 Ma (Fig. 8B). The ages overlap the 1362 ± 7 Ma and 1371 ± 14 Ma emplacement ages for the San Isabel granite (Bickford et al., 1989). Therefore we attribute the growth of metamorphic titanite to thermal perturbation and fluid flow associated with emplacement of the ca. 1365 Ma San Isabel granite batholith, the main body of which is exposed ~5–10 km from the sampled outcrops (Fig. 4).

Zircon from the G3 granite sill (J01-WC3, Fig. 8C) defines a chord with a lower intercept of 1390 ± 10 Ma, interpreted as the age of crystallization of the granitic sill. This age falls between the other two age groupings, suggesting that plutonism continued and that elevated temperatures were sustained between dynamic and magmatic events. We interpret the 1749 ± 28 Ma upper intercept for sample J01-WC3 to reflect zircon inheritance, thus providing an indirect constraint upon the protolith age for basement gneisses in the southern Wet Mountains.

**Age and Kinematics of Deformation in the Northern Wet Mountains**

The earliest preserved record of deformation in the northern Wet Mountains is in the Texas Creek domain (Fig. 3) of the Arkansas River Gorge. Siddoway et al. (2000) interpreted D1 progressive development of a penetrative cleavage (S1) and growth of cordierite (M1) wrapped by prevalent S2 foliation to have occurred during the Paleoproterozoic, broadly synchronous with emplacement of the 1663 ± 4 Ma Garell Peak pluton (Fig. 2; Bickford et al., 1989). The Texas Creek and Sheep Basin domains were folded during subsequent D2 north-south (Texas Creek) to northeast-southwest (Sheep Basin) shortening (Siddoway et al., 2000). Subsequent research has recognized a deflection of fabrics in folded gneisses around the 1474 ± 7 Ma West McCoy Gulch pluton (Fig. 2; Bickford et al., 1989) and that ca. 1430–1420 Ma monazite inclusions are present in M1 cordierite poikiloblasts in F2 fold limbs (Siddoway et al., 2002). Thus, regional heating and contraction during D2 were broadly coeval with G2 granitic magmatism during the Mesoproterozoic.

Because the Five Points Gulch shear zone truncates F2 folds of the adjacent Texas Creek domain (Fig. 3), major movement upon the shear zone development is attributed to a third phase of deformation (D3) that followed closely upon or was an outgrowth of the folding event. Our new U-Pb age for a syntectonic pegmatite dike indicates that D3 deformation in the Five Points Gulch shear zone occurred at ca. 1431 Ma. Work by Dean et al. (2002) indicates that emplacement of the 1439 ± 8 Ma Oak Creek pluton (Bickford et al., 1989; Cullers et al., 1993) was syntectonic, thus indicating that D3 deformation was widespread throughout the northern Wet Mountains. The northeast- to east-directed extensional fabrics that overprint regional foliation along the margin of the pluton (Dean et al., 2002; Siddoway et al., 2002) are generally parallel to folds within the Sheep Basin domain and lineation in the Crampton Mountain pluton (Figs. 2 and 3). Our new titanite ages indicate that the effects of
D3 were through 1422–1404 Ma in the Crampton Mountain pluton. The presence of dynamically recrystallized plagioclase and K-feldspar, quartz, and biotite reflect strain at relatively high temperatures in the northern Wet Mountains during D3 deformation.

To summarize, the structures of the northern Wet Mountains, active in the interval 1444–1431 Ma, show (1) sinistral oblique motion upon the north-south–striking Five Points Gulch shear zone, with east-northeast–directed opening indicated by the pegmatite dike array; (2) normal-sense, northeast-southwest–directed displacement on the margins of the Oak Creek pluton; and (3) north-south to northwest-southeast contraction in the Texas Creek and Sheep Basin domains, respectively, forming kilometer-to-meter-scale folds. The contrasting kinematics from coeval structures may be reconciled within a regional strain state having the maximum and minimum finite strain axes in the plane of the earth, with the intermediate axis vertical; in other words, within a transient strain state (Fig. 10, inset).

Alternatively, the formation of the Five Points Gulch shear zone, Oak Creek pluton, and pegmatite dike array, and to some extent the distribution of granite and pegmatite, were controlled by preexisting structures or mechanical anisotropies within host rocks. The margin of the Crampton Mountain batholith (Figs. 2 and 3) is an example of one such element that may control the northeast-oriented structure of the Sheep Basin domain, which mirrors the mapped geometry of the southern margin of the batholith fairly closely (Fig. 3) but contrasts with the orientation of north-northwest–striking foliation ($S_\parallel$) in the Five Points Gulch shear zone. In either case, the Mesoproterozoic ages of folding, shear zone formation, and fabric reactivation suggest that different structural domains in the northern Wet Mountains reflect varying mechanical responses to ca. 1.4 Ga subhorizontal, north-northwest–directed shortening, possibly with a significant transient component, under moderate- to high-temperature conditions.

**Age and Kinematics of Deformation in the Central and Southern Wet Mountains**

In the central Wet Mountains, direct evidence of ca. 1.4 Ga magmatism is lacking. The orientation and style of deformation is similar to that recorded in exposures farther to the south, and Siddoway et al. (2000)
suggested that many of the deformed granites are likely coreative with the G2 and G3 granites that were dated as part of this study. In exposures along Rattlesnake Gulch (Fig. 2), Jones (2005) documented syntectonic growth or recrystallization of metamorphic zircon and titanite in amphibolite between 1436 and 1390 Ma associated with fabric overprinting or reactivation. Otherwise, available age information indicates that deformation and metamorphism recorded in exposures of the central Wet Mountains is predominantly Paleoproterozoic in age (Brock and Singewald, 1968; Lanzirotti, 1988; Bickford et al., 1989).

In contrast, our new results from exposures in the southern Wet Mountains reveal that nearly all of the observed deformation occurred during the Mesoproterozoic. The earliest recognized phase of high-temperature, penetrative deformation occurred during emplacement of coarse-grained G2 granitic sills at 1435 ± 4 Ma. Magmatism was accompanied by foliation development and extensive recrystallization or new growth of metamorphic zircon in wall-rock amphibolite at 1436 ± 2 Ma. The observation that granitic sills locally cut a preexisting wall-rock foliation requires at least one phase of earlier, likely Paleoproterozoic, deformation and metamorphism; however, any isotopic record of these events has been obliterated by ca. 1.4 Ga thermal effects (Shaw et al., 2005). Gneissic G2 granite sills were affected by reverse-sense, north-northwest to south-southeast directed crustal flow. Fine-grained G3 granite sills emplaced at 1390 ± 10 Ma cut the gneissic fabric in G2 granites and wall rocks, and they exhibit the same kinematic sense; thus the duration of crustal flow deformation was on the order of 45 m.y. The 1362 ± 7 Ma San Isabel granite (Bickford et al., 1989) cuts all fabrics, and it is largely undeformed, so it provides a minimum age for all Mesoproterozoic deformation in the southern part of the range.

Circa 1.4 Ga Regional Penetrative Flow in the Lower Middle Crust

New U-Pb zircon and titanite results for tectonized granites and host gneisses prove that the Wet Mountains underwent deformation between ca. 1435 and 1360 Ma, coincident with regional granitic magmatism (Reed et al., 1993; Anderson and Cullers, 1999). Deformation was localized within subvertical shear zones in the northern part of the range, with development of cylindrical upright folds. The partitioning of strain upon discrete zones is consistent with 1.4 Ga structural styles in exposures of the Sangre de Cristo Mountains (Jones and Connelly, 2006), the Black Canyon of the Gunnison (Jessup et al., 2006), the Idaho Springs–Ralston Creek shear zone (McCoy et al., 2005), and the Homestake shear zone (Shaw et al., 2001; Selverstone et al., 2000). The shallowly to moderately dipping dynamic fabrics that are syntectonic with respect to pervasive granite sills of 1435–1390 Ma age, discovered in the southern Wet Mountains, are somewhat unique in the Mesoproterozoic record of the southern Rocky Mountains.

The relatively deep exposure of granites and migmatitic host gneisses in the southern Wet Mountains are a consequence of differential exhumation and uplift that caused northward tilting of the entire range. Evidence of this comes from comparison of geobarometry described above from the north versus south (Siddoway et al., 2000; Cullers et al., 1992). The contrast in depth of exposure is best explained by differential exhumation that caused 10°–15° of northward tilt. In addition, apatite-fission-track thermochronology from north to south across the Wet Mountains indicates substantial Cenozoic exhumation that elevated a Late Cretaceous apatite partial annealing zone and the Eocene Rocky Mountain erosion surface (Kelley and Chapin, 2004) that has been established during and after the Laramide orogeny. Taking the two factors into account, a conservative estimate for northward tilt of the Wet Mountains crystalline block is 15° to 25°. Thus, during Proterozoic time the foliation dips in the central and southern Wet Mountains would have been relatively shallow, at 35° or less.

The access to deep crustal levels in the southern Wet Mountains reveals a consistent top-to-the-south–southeast transport sense in the restored geometry of shallowly dipping fabrics that accords with the kinematics of deformation of steep foliation in mid-crustal exposures of the northern Wet Mountains. The presence of syntectonic granites that were strongly affected by the deformation provides evidence of subhorizontal crustal flow. The earliest recognized episode of pervasive flow accompanied the emplacement of coarse-grained G2 granites at 1435 Ma, and the consistent deformational record of fine-grained G3 dikes suggests that crustal flow continued until the 1390 Ma emplacement of G3 granites. The similarity of structures of older G2 and younger G3 granites indicates a stable strain state for 45 million years, suggesting long-lived, subhorizontal flow in a magma-rich environment.

IMPLICATIONS FOR Ca. 1.4 Ga TECTONIC MODELS

Granite magmatism associated with contrasting structures of the northern and southern Wet Mountains occurred during the narrow time interval of 1444–1431 Ma, with deformation at shallower crustal levels localized within discrete subvertical shear zones like the Five Points Gulch shear zone (Siddoway et al., 2000; Shaw et al., 2001; McCoy et al., 2005) or distributed throughout the Texas Creek and Sheep Basin domains as mesoscopic upright folds. An east–west–oriented zone containing abundant pegmatite and granite appears to demarcate the transition in structural styles (Siddoway et al., 2000; Collins et al., 2004). This zone of granite may have been emplaced along a rheological and thermal barrier (Fig. 10; cf. Shaw et al., 2005) at the upper boundary of the sill and dike networks at deeper levels of the southern Wet Mountains. The more coherent body of the Oak Creek pluton (Fig. 2; Cullers et al., 1993), at approximately the same crustal level has a sheeted aspect (Dean et al., 2002) that may reflect emplacement into a dilational structure controlled by mechanical anisotropies in the host gneisses (cf. McFadden et al., 2010) within a unified strain state (see above). The pegmatite and granite emplaced at the boundary may have insulated the deeper crust and helped sustain the higher temperatures at depth (Shaw et al., 2005) that are recorded by the metamorphic mineral assemblages and the new zircon and titanite ages reported here. At depth the voluminous G2 and G3 granite may have advected heat and significantly weakened the lower crust, thus permitting long-lived penetrative deformation and subhorizontal, north–norththeast to south–southeast–directed flow.

Models for intraplate deformation predict that the strength of the lower crust fundamentally influences the geometry and strain distribution within an active orogen. Royden (1996) demonstrated that a weak lower crust underlying a strong upper crust permits transmission of compressive stresses >1000 km from a convergent boundary, leading to development of a broad orogen with high average elevation but low relative relief. The spatial extent of the zone of flow in the southern Wet Mountains suggests that the pervasive sills of ca. 1435 Ma granite emplaced within high-temperature host gneisses acted to weaken the lower crust and propagate deformation across a wide region of southwest Laurentia in Mesoproterozoic time. Consequently the exposure of deep crust in the Wet Mountains merit further study as an analog for low-viscosity layers that are inferred in modern intracontinental orogenic settings like Tibet and the Altiplano (e.g., Nelson and Project INDEPTH, 1996; Brasse et al., 2002).

The flow direction for deep levels in the southern Wet Mountains is parallel with the contraction direction identified for shallower levels in the north, suggesting that north–northwest–south–southeast kinematic transport controlled the overarching pattern of deformation in the Wet Mountains. Our findings are consistent with interpretations of Nyman et al. (1994) and Nyman and Karlstrom (1997) that ca. 1.4 Ga deformation
was controlled by far-field stresses transmitted from a distant plate boundary, and the magmas may have profoundly weakened the lower crust and facilitated the propagation of deformation throughout such a broad region. However, evidence for lower crustal flow in a compressional setting for ca. 1.4 Ga magmatism seemingly conflicts with the petrogenesis and tectonic association of ferroan granites (Eby, 1990; Frost et al., 2001a). We recognize that ferroan granites are not commonly associated with convergent tectonic environments and are not known to occur within modern intracratonic orogenic settings. We also acknowledge the well-established indications of mantle involvement in ferroan granite petrogenesis (Frost et al., 2001a) and the strong association of ferroan granites and extensional or hotspot settings (Emslie, 1978; Whalen et al., 1987; Eby, 1990; Frost and Frost, 1997). But we also believe that widespread evidence for ca. 1.4 Ga deformation in exposures throughout the southern Rocky Mountains and southwestern United States, and particularly our new evidence for long-lived magma-enhanced crustal flow at deeper structural levels, warrants consideration as well.

Shaw et al. (2005) speculated that topographically driven syncontractional extension at shallower crustal levels at ca. 1.4 Ga could reconcile regional structural evidence for shortening with the geochemical characteristics of coeval granites. Modern orogens and orogenic plateaus commonly display evidence for synchronous shortening and extension both parallel and perpendicular to the orogen (e.g., Burchfiel et al., 1992), and the apparent contrast between shortening in the southwestern United States and extension in the granite-rhyolite provinces of the mid-continent region might simply reflect contrasting levels of exposure. Emplacement of mantle-derived tholeiite required for generating ferroan granites could be related to asthenospheric upwelling driven by thermal or convective removal of an organically thickened lithosphere (e.g., Houseman et al., 1981) or by emplacement of a large mantle plume (Hoffman, 1989; Frost and Frost, 1997; Ferguson et al., 2004). The former mechanism is a process believed to occur quite commonly in convergent orogenic systems (e.g., Collins, 1994; Cloos, 2003) and has been inferred along the eastern margin of Laurentia during approximately the same time (Rivers, 1997). The latter mechanism was likely responsible for producing extremely ferroan and alkalic granites at ca. 1.4 Ga in southwestern Wyoming (Frost and Frost, 1997).

Alternatively, the indications of transcurrent strain in the northern Wet Mountains, together with regional evidence for localized extension (e.g., Kirby et al., 1995) and oblique movement along ca. 1.4 Ga shear zones (e.g., Silverstone et al., 2000; Shaw et al., 2001; Jessup et al., 2006), suggest that regional shortening at ca. 1.4 Ga may have involved a significant transpressional component. Ferroan granites may be associated with transcurrent settings (Sylvestor, 1989; Düzgören-Aydin et al., 2001; Deering et al., 2008), and a transpressional strain field would allow for structures indicating shortening and simultaneous tholeiitic dike and underplating in the lower crust. The spatial association of shear zones and ca. 1.4 Ga granites suggests that these structures may have conveyed magma upward from sites of underplating, differentiation, and additional melt generation in the lower crust (Fig. 10; Nyman et al., 1994). Dilation or extension may have occurred locally in areas where preexisting crustal fabrics were oriented at an angle to the regional northeast-striking structural grain (e.g., Kirby et al., 1995; Nyman and Karlstrom, 1997; Karlstrom and Humphreys, 1998; Dean et al., 2002; Jessup et al., 2005).

CONCLUSIONS

Several important insights emerge from new geologic and geochronologic data from an oblique Proterozoic crustal section in the Wet Mountains, Colorado:

1. Mid-crustal deformation in the northern part of the range involved folding, shear zone formation, and development of subvertical fabrics between 1431 and 1404 Ma. Strain was partitioned in discrete structural domains, owing to varying mechanical responses to ca. 1.4 Ga subhorizontal, north-northwest–directed shortening or transcurrent strain.

2. At deeper levels, granite sills and dikes intruded migmatitic host gneiss that underwent pervasive subhorizontal lower crustal flow 1435–1390 Ma, with south-southeast–directed transport, resulting in widespread, gently dipping fabrics.

3. The contrasting deformation styles and plutonism in the northern and southern Wet Mountains were contemporaneous and broadly kinematically compatible, with minor differences attributable to increasing depth of exposure from north to south across the range or differential movements during poly-stage exhumation.

4. Metamorphic temperatures were sufficiently high to induce metamorphic growth of titanite and zircon, and thus were sufficient to create a weak, low-viscosity lower crust that would flow in response to dynamic or gravitational stresses.

Furthermore, the kinematics of mid- to lower crustal structures of the Wet Mountains is in accord with results over a broad region and thus lend support to the identity of the Wet Mountains as a deeply exhumed analog for the mid-crustal, low-viscosity layers of the type that are inferred to exist in modern intracratonic orogenic settings. Our findings are consistent with an orogenic setting for widespread granitic magmatism at ca. 1.4 Ga and further suggest that the granites may have played a key role in weakening the lower crust, thus allowing deformation to propagate over such a broad region. More work is needed to better understand the geochemistry and petrogenesis of granites exposed at deep crustal levels in the Wet Mountains and to assess the extent and geometry of transient deformation locally and throughout the surrounding region in an effort to reconcile the contrasting interpretations of the tectonic environment for the remarkable extent of potassic, ferroan granites at ca. 1.4 Ga.

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