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**Notes**

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# *Proterozoic metamorphism and deformation in the northern Colorado Front Range*

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## ABSTRACT

**Paleoproterozoic supracrustal rocks in the region near Big Thompson Canyon, northern Colorado, have long been recognized as a spectacularly exposed example of regionally zoned metamorphism, preserving an apparently complete sequence from biotite- to migmatite-zones. Due to its location and relatively easy access, the Big Thompson Metamorphic Suite has also provided a valuable field-based educational experience for universities and colleges all along the Front Range and from elsewhere. In addition to a number of other studies, the pioneering work of William Braddock and graduate students from the University of Colorado resulted in more than a dozen M.Sc. and Ph.D. theses from the 1960s to the 1990s. Despite the volume of ground-breaking science conducted on these rocks in the past, there remain a number of fundamental questions regarding the metamorphic history and overall tectonic significance of many of the observable features. Several lines of evidence suggest there is potential for a complex tectonometamorphic history that likely spans from ~1.8 to 1.4 Ga. These include: thermochronologic and geochronologic data supporting multiple thermal and magmatic episodes, structural evidence for multiple deformation events, multiple generations of typical Barrovian minerals (e.g., staurolite), and the widespread occurrence of minerals not commonly associated with a classic Barrovian sequence (e.g., andalusite, cordierite). One purpose of this fieldtrip is to foster new ideas and stimulate new research directions that will utilize the Big Thompson Metamorphic Suite, and the Colorado Rockies in general, as field laboratories for better understanding fundamental orogenic processes.**

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## TRIP OVERVIEW

This guide aims to introduce Earth scientists to a classic area of northern Colorado geology. The field trip covers a series of stops along the Big Thompson Canyon on U.S. 34 and the North Fork of the Big Thompson River on County Road 43 with one stop on Storm Mountain Drive above the community of Cedar Park. This route intersects a series of mineral isograds that are conventionally thought to represent a prograde sequence in metasediments from biotite-chlorite grade to migmatite. Mapped isograds that are crossed include garnet-in, staurolite-in, andalusite-in, sillimanite-in, K-feldspar-in. and migmatite-in. The trip is structured around the following key questions. (1) Does the sequence of "isograds" represent a single cycle or multi-cycle Pressure-Temperature (P-T) evolution? (2) What are the absolute and relative ages of deformation events with respect to P-T evolution and porphyroblast growth? (3) What roles did ~1.4 Ga magmatism and deformation play in the geologic history of northern Colorado? (4) To what extent can the Pressure-Temperature-time-Deformation (P-T-t-D) paths of these rocks be constrained and how do the rocks fit into the tectonic evolution of northern Colorado?

All stops are between 5200 and 8000 feet elevation. Stop 1 is near the mouth of Big Thompson Canyon in a section commonly called "The Narrows." This is near the boundary of the garnet-in isograd, and features best observed here include compositional layering interpreted as bedding (Tweto, 1987) and numerous meter-scale tonalite sills. Stop 2 is accessed by parking at Viestenz-Smith Mountain Park and crossing to the north side of the river. Fresh staurolite and garnet can be observed at this stop along with retrograded pseudomorphs of earlier minerals whose potential identity will be discussed. This is where the possibility of a polymetamorphic history will first be introduced. Stop 3 is at a "big curve" on U.S. 34, where features to observe include graded textures indicating overturned bedding, crenulation cleavage, retrograded staurolite porphyroblasts, and tonalite and granitic pegmatite dikes and sills. New topics to discuss here will include relative and absolute timing of deformation phases. Stop 4 is at Midway and serves as a lunch stop. Many of the earlier described features are also visible and additional features include meter-scale boudinage of tonalite sills, possible $F_1$ folds, and andalusite porphyroblasts. Stop 5 is on Storm Mountain Drive and is the highest elevation stop. The sillimanite-in isograd is near, and clusters of outcrops display all of the earlier described porphyroblastic phases and pseudomorphs, and additionally include sillimanite and cordierite. Multiple generations of crenulation cleavages will also be observed. Stop 6 is near the community of Glen Haven in the K-feldspar zone and close to the mapped migmatite isograd. Throughout the day, new items for discussion will be introduced and the most interesting and debatable topics will be revisited.

## PROTEROZOIC TECTONICS IN THE NORTHERN COLORADO FRONT RANGE

### Regional Overview

Precambrian basement rocks in Colorado represent the northernmost part (present day reference frame) of a >1000 km wide orogenic belt that records the generally southward growth of the North American continent from ~1.8 to 1.0 Ga (e.g., Whitmeyer and Karlstrom, 2007). The major provinces, from oldest to youngest, are commonly referred to as the Mojave (~2.4–1.7 Ga), Yavapai (~1.8–1.7 Ga), Mazatzal (~1.7–1.6 Ga), Granite-Rhyolite (~1.5–1.3 Ga), and Grenville (~1.3–1.0 Ga) Provinces. The Mojave and Yavapai Provinces (Fig. 1A) are traditionally distinguished based primarily on isotopic evidence for a cryptic but significant pre-1.8 Ga (and possibly Archean) component to the former in the subsurface (e.g., Wooden et al., 1988), whereas the timing of major magmatism and deformation (~1.78–1.68 Ga) is similar. The boundary between these two provinces is also not well defined but is generally considered to lie in northernmost Colorado (Fig. 1A). The Yavapai-Mazatzal province boundary, as well as the northernmost extent of Mazatzal-aged deformation, is equally ill constrained but the boundary is generally considered to lie in a wide transition zone beginning in south-central Colorado (Shaw and Karlstrom, 1999), just north of the Wet Mountains (Fig. 1A). Some workers refer to all of the Proterozoic rocks in Colorado as the "Colorado Province" (Reed et al., 1987; Sims and Stein, 2003).

Regardless of the "provincial" label, exposed terranes in northern Colorado are conventionally thought to represent juvenile island arc terranes accreted to the southern margin of the Wyoming craton during the interval between ~1.78 and 1.70 Ga (Condie, 1982; Reed et al., 1987; Bowring and Karlstrom, 1990). The earliest and most well recognized suture is the Cheyenne Belt in southernmost Wyoming, which separates the Archean craton to the north from Proterozoic provinces to the southeast (Karlstrom and Houston, 1984; Chamberlain et al., 2003). The timing of this continent-oceanic arc collision, termed the Medicine Bow Orogeny, is constrained to between ~1.78 and ~1.75 Ga (Chamberlain, 1998). The accreting terrane is commonly referred to as the Green Mountain arc, an ~1.78 Ga suite of mafic and felsic igneous and associated metasedimentary rocks that crop out in southern Wyoming and northern Colorado (Reed et al., 1987; Tyson et al., 2002; Jones et al., 2011). The Farwell Mountain–Lester Mountain zone in the Park Range of northern Colorado (FM-LM in Fig. 1A) has been proposed as a possible suture bounding the Green Mountain arc to the south based on seismic reflections and changes in lithology and metamorphic grade (Fig. 1A; Tyson et al., 2002; Morozova et al., 2005). Paleoproterozoic rocks in the southern Park Range and Front Range are commonly considered part of the Rawah arc, the two major intrusive constituents being the ~1.72–1.71 Ga Rawah and Boulder Creek batholiths (Fig. 1B; Reed et al., 1987; Premo and Van Schmus, 1989; Tyson et al., 2002; Premo et al., 2010a).

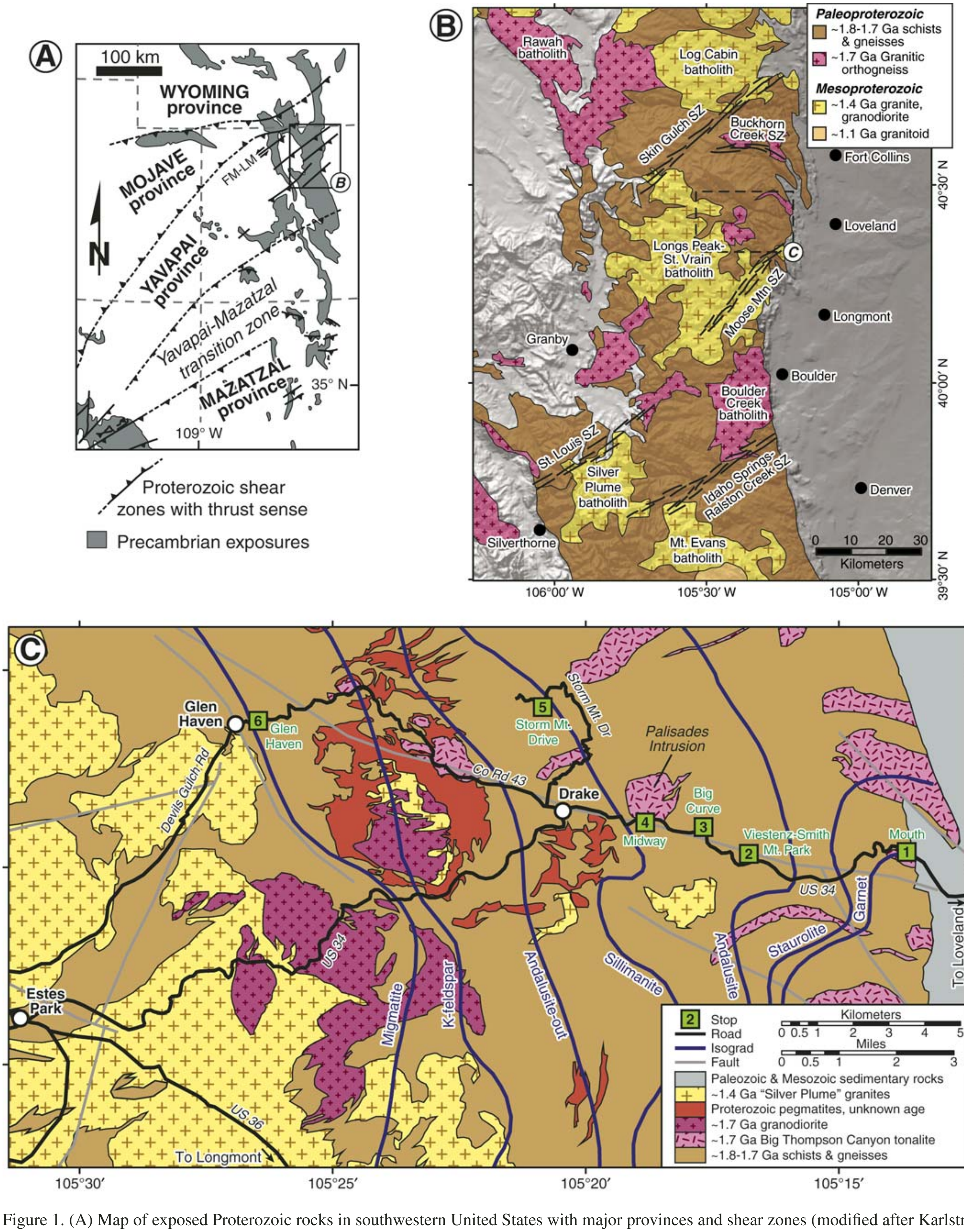



Figure 1. (A) Map of exposed Proterozoic rocks in southwestern United States with major provinces and shear zones (modified after Karlstrom and Williams, 2006). FM-LM: Farwell Mountain–Lester Mountain zone. (B) Simplified geological map of Proterozoic exposures in the Front Range (modified after Tweto, 1979). (C) Geologic map of Big Thompson Canyon and surrounding areas with isograds and field trip stops shown (simplified from Cole and Braddock, 2009).

Several new questions have recently been raised that may have relevance to the nature and timing of deformation and metamorphism in the Big Thompson Canyon region. These include: (1) Do the rocks of the northern Yavapai (or Colorado) province truly represent discrete island arc terranes successively accreted to Laurentia, or were they were built on a previously extended continental crustal substrate? (2) How far north does the real "Mazatzal deformation front" extend? (3) What is the extent and tectonic significance of ~1.4 Ga magmatism, metamorphism, and deformation? Several recent studies have challenged the conventional view of a simple southward younging juvenile arc accretion model by pointing to the bimodality and zircon-Hf isotopic composition of many of Colorado's volcanic associations. This suggests that melting of continental crust was likely involved, which is supported by the recognition of late Archean and ~1.85 Ga detrital zircon in several Colorado localities (Selverstone et al., 2000; Hill and Bickford, 2001; Cavosie and Selverstone, 2003; Sims and Stein, 2003; Plymate et al., 2005; Bickford et al., 2008; Jones et al., 2011). This complicates the traditional distinction between the Mojave and Yavapai Provinces stated earlier. Hill and Bickford (2001) propose that much of Colorado might be underlain by a southwestern extension of the ~1.9–1.8 Ga Trans-Hudson orogen that experienced "Basin & Range"-style extension prior to construction of the ~1.78–1.70 Ga arc systems. Cavosie and Selverstone (2003) propose that ophiolitic fragments exist in the Buckhorn Creek shear zone, west of Fort Collins (Fig. 1B) and interpreted these to represent a reactivated oceanic transform that initially developed in a backarc setting between the Wyoming craton and a thinned continental fragment to the south. Others have suggested that the Green Mountain arc was continental and experienced a rifting event shortly after its ~1.78 Ga formation to produce the "Poudre Basin" within which much of the metasedimentary rocks in northern Colorado were deposited (Dewitt et al., 2010; Premo et al., 2010b).

The "traditional" view is that the northernmost limit of "Mazatzal" age (~1.65–1.60 Ga) deformation and metamorphism lies in southern Colorado (e.g., "transition zone" of Shaw and Karlstrom, 1999). However, recent studies document reactivated deformation near the Cheyenne belt in this age range, including widespread metamorphic zircon and monazite associated with an inferred contractional episode at ~1.63 Ga (Jones et al., 2010a) and brittle-ductile transpressional deformation at ~1.60–1.59 Ga (Duebendorfer et al., 2006). Similarly, the tectonic significance of widespread Mesoproterozoic (~1.4 Ga) granitoids that occur throughout the southwestern U.S. has long been a subject of debate. Originally considered anorogenic (Anderson, 1983; Bickford and Anderson, 1993), many of the intrusions are now recognized to have accompanied significant deformation in a number of localities from California, Arizona, New Mexico, and Colorado (Nyman et al., 1994; Selverstone et al., 2000; McCoy et al., 2005; Jones et al., 2010b). Several shear zones in northern Colorado are known to have been at least partly active at ~1.4 Ga (e.g., Moose Mountain shear zone; Selverstone et al., 2000; Idaho Springs–Ralston and St. Louis shear zones; McCoy et al., 2005). Most recently, much of the previously presumed Paleoproterozoic aluminosilicate "triple-point" metasedimentary domain in northern New Mexico is now known to have ~1.49–1.46 Ga depositional ages, thus requiring ~1.45 Ga burial and widespread mid-crustal metamorphism ("Picuris Orogeny"; Daniel and Pyle, 2005; Daniel, 2012; Daniel, 2013; Daniel et al., 2013, this volume). These studies raise the question of whether similarly aged deformation and metamorphic events might be as yet unrecognized in northern Colorado.

## Big Thompson Metamorphic Suite

The Big Thompson Metamorphic Suite is possibly the only group of rocks in the Colorado Rockies that preserves mappable metamorphic isograds. William Braddock and a number of his students completed some of the earliest work in and around the canyon (e.g., O'Connor, 1961; Calvert, 1963; Gawarecki, 1963; Curtin, 1965; Nutalaya, 1964; Nutalaya, 1966; Bucknam, 1969; Punongbayan, 1972; Nesse, 1977; Cole, 1977; Barovich, 1986). The isograds define an arcuate pattern with assemblages reflecting an increase from biotite+chlorite grade in the east to migmatite in the west (Fig. 1C). It has been suggested that these isograds define a set of synformal surfaces whose axis plunges eastward (Nesse, 1984), perhaps assuming the highest temperature metamorphic zones form the structurally deepest exposures. The Big Thompson Metamorphic Suite is also unique in the sense that significant tracts of low to moderate grade (biotite-, garnet-, staurolite-) rocks with relict primary sedimentary features are preserved, whereas most other Proterozoic supracrustal rocks in the Front Range experienced higher grades of metamorphism and complete overprinting of primary structures.

### *Supracrustal Rocks*

The Big Thompson Metamorphic Suite is dominated by layered metasedimentary and likely metavolcanic rocks, including pelitic phyllite and schist, metaconglomerate, quartzite, quartzo-feldspathic gneiss, and minor amphibolite and calc-silicate schist, the detrital components of which are variably interpreted to have been derived from the Archean southern Wyoming craton, a now buried remnant extension of the ~1.8 Ga Trans-Hudson orogen, and/or the Green Mountain arc (e.g., Reed et al., 1987; Aleinikoff et al., 1993; Reed, 1993; Selverstone et al., 2000; Hill and Bickford, 2001; Dewitt et al., 2010). A total thickness of the sedimentary sequence is estimated at 12,000 feet (3.65 km; Braddock, 1970). At the lower metamorphic grades (east), the rocks are turbidites with preserved sedimentary structures including graded bedding, cross-bedding, scour-and-fill structures and thin conglomerate lenses (O'Connor, 1961; Calvert, 1963; Gawarecki, 1963; Curtin, 1965; Braddock, 1970). These features have been interpreted to represent a shelf or reworked submarine-fan in either a foreland or backarc depositional setting (Condie and Martell, 1983; Reed et al., 1987; Cole and Braddock, 2009). Amphibolite and quartzo-feldspathic rocks are locally interlayered with the metasediments and interpreted as metavolcanic rocks (Gawarecki, 1963; Pearson, 1980; O'Neill, 1981; Schroder, 1995) with U-Pb zircon crystallization ages of ~1.79–1.76 Ga (Premo et al., 2007). At least one sample from the southern Big Thompson Metamorphic Suite indicates a significant Archean detrital component that is interpreted to have been derived from the Wyoming craton (Selverstone et al., 2000). The youngest detrital zircon from this sample is ~1.76 Ga and provides an approximate maximum depositional age (Selverstone et al., 2000).

### *Intrusive Rocks in the Region*

The two major groups of intrusive rocks occurring in the region are, broadly, the ~1.7 Ga "Routt Plutonic Suite" and the ~1.4 Ga "Berthoud Plutonic Suite" (Tweto, 1987). The former represents a suite of Paleoproterozoic calc-alkaline intrusive rocks that range in composition from monzogranite to tonalite/trondhjemite. The suite includes the Boulder Creek granodiorite, which has a U-Pb zircon date of 1714 ± 5 Ma (Premo and Fanning, 2000) and a more recent composite date of 1713 ± 4 Ma (Premo et al., 2010a). The Palisade tonalite/trondhjemite intrusion has an upper intercept U-Pb zircon age of 1726 ± 15 Ma (multi-grain fractions; Barovich, 1986). Intrusive bodies observed at stops in this guide are typically medium-grained, light gray, two mica tonalite to granodiorite dikes and sills that are similar in composition to the Palisade intrusion and are collectively referred to as Big Thompson Canyon tonalite in this guide (Fig. 1C).

A second major phase of intrusive activity affected Colorado, New Mexico, and Arizona at ~1.48–1.38 Ga, which in the Front Range is grouped into the "Berthoud Plutonic Suite" (Tweto, 1987). In the Big Thompson Canyon area these are dominated by batholiths of "Silver Plume–type" granite, granodiorite, quartz diorite and pegmatite, which form irregular batholiths, ovoid plutons and dikes (Boos and Boos, 1934). In the northern and central Front Range, the largest intrusive body in this group is the two-mica monzogranite to syenogranite of the Longs Peak–St. Vrain batholith (Cole, 1977; Anderson and Thomas, 1985).

Muscovite-bearing alkali-feldspar granite pegmatite dikes and sills also occur throughout the Big Thompson Metamorphic Suite and can have a myriad of notable minor minerals including biotite, tourmaline, garnet, and beryl. The pegmatites commonly grade into regions of aplitic texture. While most of the pegmatites appear largely undeformed, some display local evidence for solid-state deformation. Pegmatites are thought to be associated with all of the above-discussed intrusive suites, but no general field criteria for determining their association to 1.7 Ga versus 1.4 Ga intrusions has been established (Cole and Braddock, 2009).

### *Structures and Deformation History*

On the basis of reversals in graded bedding and symmetrically mappable units in the lower grade rocks, the Big Thompson Metamorphic Suite preserves isoclinal folds with wavelengths of several kilometers. The largest and most certain of these $F_1$ folds is an ENE trending overturned syncline whose axial trace occurs several kilometers north of Big Thompson Canyon (O'Connor, 1961; Calvert, 1963; Gawarecki, 1963; Curtin, 1965; Braddock, 1970). Axial planar to these $F_1$ folds is a penetrative $S_1$ cleavage that is subparallel to bedding ($S_0$) except locally where it can be observed as axial planar to outcrop scale $F_1$ folds expressed in the $S_0$ layering. Braddock (1970) suggested that the formation of $S_1$ as a slaty cleavage may have initially formed in an unconsolidated state in accordance with the "dewatering hypothesis" of Maxwell (1962). However, subsequent work has largely ruled out many of the inferred deformation mechanisms for the dewatering hypothesis in favor of solution driven cleavage development (e.g., Beutner, 1978). Biotite defining the $S_1$ cleavage in the Big Thompson Metamorphic Suite suggests conditions during $D_1$ reached at least the greenschist facies.

Multiple post-$D_1$ fabric-forming and folding events affected the Big Thompson Metamorphic Suite. Most studies have described younger planar fabrics as crenulation cleavages, although it is relatively rare to see evidence for multiple generations in the same outcrop (Stop 5 will be an example). For most of the region covered in this guide, from Stop 5 eastward, there is essentially one well-developed crenulation cleavage observable in the more micaceous units. This cleavage generally strikes NW-SE, dips either SW or NE, and is commonly axial planar to outcrop- and kilometer-scale open to tight moderately SW-plunging folds (O'Connor, 1961; Gawarecki, 1963; Nutalaya, 1964; Curtin, 1965; Bucknam, 1969). For the purposes of this guide, these structures will be referred to as $D_3$-$S_3$-$F_3$, with an additional subscript of $S_{3a}$ and $S_{3b}$ introduced at Stop 5. $D_2$ structures (folds and crenulation cleavage) have similar E-W to NE-SW trending elements where they are primarily preserved in the northern and westernmost Big Thompson Metamorphic Suite (Braddock and Cole, 1979[1]; Hutchinson and Braddock, 1987; Cole and Braddock, 2009). In the region around Big Thompson Canyon the authors have observed no confirmed elements of $D_2$ structures. Barovich (1986) describes $S_2$ cleavage in the area around Palisade Mountain (between Stops 3 and 5), but acknowledges that the evidence there is scarce and geometrically indistinguishable from $S_1$. Additional generations of crenulation cleavage and folds have locally been recognized in parts of the Big Thompson Metamorphic Suite but appear to be weakly developed (e.g., Calvert, 1963; Curtin, 1965; Nutalaya, 1964; Shah and Bell, 2012). Intersection lineations between the various planar fabrics and layering are common.

Two prominent kilometer-scale ductile shear zones form the approximate northern and southern margins of the main body of the Big Thompson Metamorphic Suite (Fig. 1B). The Buckhorn Creek shear zone is an approximately east-striking and steeply dipping zone of mylonite up to 1 km wide (Cavosie and Selverstone, 2003). It is composed of a variety of mylonitized mafic and intermediate gneiss interpreted as a tectonic mélange emplaced during a contractional episode of deformation but originating as an oceanic transform (Cavosie and Selverstone,

[1]This guide is available as item 2013328 in the GSA Data Repository at http://www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org.

2003). The shear zone is reported by these workers to separate middle amphibolite-facies, andalusite-bearing schists to the south from sillimanite-bearing and higher-grade gneisses to the north. However, previous workers have found little evidence for structures of similar magnitude in adjacent regions to the west (e.g., Nesse and Braddock, 1989; W. Nesse, 2013, personal commun.). The Moose Mountain shear zone is a northeast-striking and steeply south-dipping zone of reverse sense mylonite up to 2 km wide (Hodgins, 1997; Selverstone et al., 2000). The zone is interpreted to have been active at both ~1.7 Ga and ~1.4 Ga, the latter evidenced by the fact that much of the most well-developed mylonite affects the ~1.4 Ga Longs Peak–St. Vrain granite. Activity at ~1.7 Ga on both shear zones has been inferred based on the restricted occurrence of ~1.73 Ga tonalite and trondhjemite to the block between the shear zones, in contrast to the widespread occurrence of ~1.71 Ga intrusions of the Boulder Creek batholith throughout northern Colorado (Selverstone et al., 2000; Cavosie and Selverstone, 2003). Further, detrital zircon populations in the supracrustal rocks differ on either side of the Moose Mountain shear zone (Selverstone et al., 2000).

### *Isograds and Metamorphic History*

The metamorphic evolution of the Big Thompson Metamorphic Suite is complex, despite the apparent simplicity presented by concentric mineral isograds (Cole and Braddock, 2009; Fig. 1C). The significance of the isograds, the mineralogical evolution, mineral textures, and the relationships between deformation events and porphyroblast generations is still a subject of continued discussion and conjecture. The interpretation of textural relationships and the applicability of thermobarometric calculations are further complicated by widespread retrogression of many of the isograd indicator minerals (e.g., garnet, staurolite; Cole, 1977; Cole and Braddock, 2009), as well as the occurrence of several generations of the same minerals (e.g., garnet, staurolite, andalusite, cordierite).

Only a limited portion of previous thesis and dissertation work on the petrology of the Big Thompson Metamorphic Suite has been published (e.g., Braddock, 1970; Nesse, 1984). These theses and the published work characterized the geometry of the metamorphic isograds (Fig. 1C), and explained the sequence of successive mineral reactions and porphyroblast growth in terms of a single low-pressure P-T trajectory (~0.4–0.5 GPa; Nesse, 1984). Interlayered with the metapelites are common domains of graywacke and more quartz-rich rocks, which are less reactive to subtle changes in P-T conditions. Therefore, the following description is predominantly based on rocks with more pelitic compositions (e.g., knotted micaschist, biotite schist, and porphyroblastic biotite schist; Cole and Braddock, 2009).

The lowest metamorphic grade rocks preserved occur in the canyon mouth and are dominated by biotite-muscovite-chlorite-bearing phyllite, which in more mica-rich layers locally contain biotite porphyroblasts (and poikiloblasts) up to 2 cm in size. Biotite porphyroblasts are commonly random in orientation, but may also show a general alignment with $S_2$ or $S_3$ crenulation cleavage (Nutalaya, 1966).

With increasing distance west into the canyon, almandine-rich garnet appears in the more pelitic compositions and occurs as porphyroblasts up to 2 mm in size. The mapped garnet-in isograd occurs close to the mouth of Big Thompson Canyon (Fig. 1C). This isograd generally coincides with the disappearance of prograde chlorite. Chlorite is locally present at higher grade as a retrograde mineral. Garnet generally increases in size in higher-T zones, and is commonly partially to completely retrogressed to biotite+chlorite (Nesse, 1984; Selverstone et al., 1997).

The mapped staurolite-in isograd is crossed in the canyon at ~2.9 km (1.8 mi) from the mouth. Within rocks mapped as above the staurolite-isograd, fresh staurolite is rare, and is commonly pseudomorphed by fine-grained muscovite and chlorite. Rare staurolite crystals occur in the cores of muscovite+chlorite pseudomorphs. The pseudomorphs are typically 1–5 cm in size and retain the staurolite habit, including common cross-twins and lozenge crystal shape. The fresh staurolite that occurs in the cores of larger pseudomorphs has been variably interpreted as either relicts of partially retrogressed staurolite (O'Connor, 1961; Nutalaya, 1966; Punongbayan, 1972) or as a new second generation of staurolite (Shaw et al., 1999). However, the euhedral shape of these crystals supports this latter hypothesis. Relict staurolite overgrows $S_1$ and locally is reported to have overgrown younger crenulation cleavages (Punongbayan, 1972).

The mapped andalusite-in isograd is crossed ~3.4 km (2.1 mi) from the canyon mouth. Andalusite occurs as large porphyroblasts, commonly 2–10 cm but locally up to 20 cm in size, and two textural types have been described (e.g., Punongbayan, 1972). The first are relatively inclusion-free porphyroblasts that exhibit optical zoning (pleochroic pink cores) and were interpreted to pre-date sillimanite. The second are inclusion-rich and commonly preserve crenulated inclusion trails of biotite and muscovite, with reports of sillimanite and staurolite inclusions (Nutalaya, 1966; Punongbayan, 1972). This second generation of andalusite could reflect a second andalusite-forming reaction after staurolite breakdown, and has been interpreted to post-date sillimanite and to reflect growth either synchronous with $D_3$ (Punongbayan, 1972) or post-dating $D_3$ (Nutalaya, 1966). The absence of sillimanite inclusions in one textural type of andalusite is not definitive proof of two andalusite growth stages, before and after sillimanite. Therefore, it remains possible that the two textural generations of andalusite represent a single growth event; the different textures may reflect a rock composition controls (e.g., blocky andalusite in knotted mica schist versus poikilitic in quartzo-feldspathic micaschist) and/or variable growth rates. Alternatively, the presence of andalusite at higher-grades past the sillimanite-isograd could be interpreted as evidence of sillimanite retrogression (Nesse, 1984).

The mapped sillimanite-in isograd occurs 9.2 km (5.7 mi) from the canyon mouth (Fig. 1C), west of Midway. It initially appears as fibrolite, locally occurring in matrix domains and commonly associated with aggregates or porphyroblasts of biotite or muscovite. With increasing apparent metamorphic grade, sillimanite forms larger (several millimeter-sized) clusters of fibrolite, and becomes increasingly prismatic (Punongbayan, 1972). It can be argued that the first sillimanite grew at the expense of andalusite. However, sillimanite is commonly found associated with biotite or prograde muscovite, suggesting mica serves as a nucleation site for sillimanite. A second generation of sillimanite grew during the melt-in reaction (see below), but distinguishing between the two generations in the field is likely difficult. A short transition zone occurs immediately after the appearance of sillimanite, where staurolite apparently coexists metastably with sillimanite. This apparent coexistence of staurolite and sillimanite likely reflects the previous existence of andalusite enclosing staurolite. Similarly, andalusite also persists for some distance above the sillimanite-in isograd (Fig. 1C), but is eventually lost from the assemblage. Immediately north of the Skin Gulch shear zone (Fig. 1B), large andalusite porphyroblasts are reported in sheared and partially annealed rocks, and interpreted to have grown post-shearing and through sillimanite retrogression (Nesse, 1984; W. Nesse, 2013, personal commun.), further supporting an interpretation for the presence of retrograde andalusite.

Throughout the sillimanite zone, muscovite abundance in metapelitic rocks gradually decreases, and prior to reaching the zone of partial melting, muscovite is largely lost from the rocks. It is replaced by sillimanite/andalusite and K-feldspar (var. microcline) with the K-feldspar-in isograd crossed on County Road 43 at ~19 km (~12 mi) from the mouth of the canyon. Nonetheless, some large muscovite books are observed past the K-feldspar-in isograd, and are likely the result of sillimanite or K-feldspar retrogression. Throughout the metamorphic grade increase, the grain size regularly increases and reaches a maximum in the K-feldspar / migmatite zone with large millimeter- to centimeter-sized matrix crystals and larger porphyroblasts.

Throughout the intermediate-temperature domains of the canyon, cordierite is recorded, in some cases apparently locally intergrown with staurolite, biotite and muscovite (Cole and Braddock, 2009). In other cases, textures suggest it post-dates staurolite, sillimanite and andalusite as a retrograde phase (Curtin, 1965; Punongbayan, 1972). Cordierite is locally pinitized (alteration to muscovite, biotite, chlorite and/or clay minerals). In the most fertile rock compositions, rocks reach the point of partial melting near Glen Haven at ~22.7 km (14.1 mi) from the canyon mouth (Fig. 1C).

The precise P-T conditions for various parts of Big Thompson Metamorphic Suite are unclear. Earlier workers estimated conditions, based on limited mineral stability constraints, to have evolved from <400 °C up to ~700 °C at 0.4–0.5 GPa (Nutalaya, 1966; Punongbayan, 1972). Cole (1977) suggested peak conditions recorded in migmatite to be around 0.55 GPa and 700 °C, whereas Munn and Tracy (1992) and Munn et al. (1993) proposed a higher pressure of 0.7 GPa. Nesse (1984) suggested the maximum pressure of the sillimanite+K-feldspar-isograd is below 0.4 GPa to account for the disappearance of muscovite before the migmatite-zone, similar to the 0.35–0.4 GPa and ~540 °C results of Shah and Bell (2012) for rocks proximal to the andalusite isograd. Whereas all minerals permit a constant Buchan-type low-P evolution, garnet-plagioclase thermobarometry has been used to suggest a medium- to high-P stage (up to 1.0 GPa) during a possible Barrovian-type first metamorphic event (Hodgins, 1997; Siddoway et al., 2000). No kyanite as ever been identified in Big Thompson Metamorphic Suite and has led many others workers to rule out a higher-pressure event (e.g., Nesse, 1984; Cole and Braddock, 2009).

### *Geochronology and Thermochronology*

Several approaches have been used in attempts to date the deformation and metamorphism of the Big Thompson Metamorphic Suite. First, the youngest detrital zircon at 1758 ± 26 Ma (Selverstone et al., 2000) establishes a maximum age for the first deformation ($D_1$) and the onset of metamorphism. Barovich (1986) interpreted emplacement of the 1726 ± 15 Ma Palisade tonalite to have re-oriented, and thus post-date, $S_1$ and $S_2$ cleavages, but to pre-date the $S_3$ cleavage. Based on concordant to locally discordant contacts with surrounding layered rocks, local boudinage, and the presence of foliations within some bodies, Braddock and Cole (1979) preferred to more generally consider emplacement of the tonalite to have been syn-kinematic with respect to $D_2$ and $D_3$. Barovich's (1986) conclusions appear to be broadly consistent with a more recent microstructural study by Shah and Bell (2012), who suggested deformation at ~1.76 Ga, ~1.72 Ga, and ~1.67 Ga based on U-Th-total Pb dating of monazite for the first three of four sets of foliation intersection axes.

Finally, Shaw et al. (1999) conducted $^{40}Ar$-$^{39}Ar$ thermochronology of muscovite, biotite and hornblende to constrain the cooling history and the possible existence of multiple thermal events. Ar-signatures from muscovite and biotite both give ages of ~1.4 Ga, whereas hornblende partially retains an older ~1.7 Ga signature, with apparent ages between ~1.6 and 1.39 Ga based on highly disturbed step-heating age spectra. Thermal modeling to account for these Ar-ages is consistent with a brief thermal overprint that reached 500–550 °C at ~1.4 Ga, and led these workers to suggest that some of the late-stage porphyroblasts may have grown at that time. This appears to be in part corroborated by Shah and Bell (2012) who report ~1.4 Ga monazite inclusions in some andalusite and cordierite porphyroblasts.

## ROAD LOG AND STOP DESCRIPTIONS

### Stop List and Cumulative Driving Distances (from Mouth of Big Thompson Canyon)

| | | |
|---|---|---|
| Stop 1 | 0.0 km (0.0 mi) | Mouth of Big Thompson Canyon, U.S. 34 |
| Stop 2 | 6.1 km (3.8 mi) | Viestenz-Smith Mountain Park, U.S. 34 |
| Stop 3 | 8.0 km (5.0 mi) | Big curve, U.S. 34 |
| Stop 4 | 10.0 km (6.2 mi) | Midway, U.S. 34 (Lunch) |
| Stop 5 | 20.0 km (12.4 mi) | Storm Mountain Drive near Hyatt Mine |
| Stop 6 | 37.8 km (23.5 mi) | Glen Haven, Co Rd 43 |

**Stop 0. Devils Backbone Open Space Parking Lot**
(UTM NAD83 Zone 13T 487103, 4473468)

The Devils Backbone Open Space parking lot is located 500 m (0.3 mi) north of U.S. 34 in Loveland, Colorado, on Hidden Valley Drive ~13.4 km (8.3 mi) west of Interstate 25. No Proterozoic rocks can be viewed here, but the location provides vault toilets and an outdoor classroom for pre-trip lectures or overviews. The geology of Devils Backbone is of note as Permian through Cretaceous rocks are present, folded during the Laramide orogeny into the hanging wall anticline of a fault propagation fold associated with the west directed Milner Mountain Fault (Erslev and Holdaway, 1999).

**Stop 1. Big Thompson Canyon Mouth**
(UTM NAD83 Zone 13T 480802, 4474614)

Parking for Stop 1 is on the north side of U.S. 34 ~8.0 km (5.0 mi) west of Stop 0 adjacent to a river gauging station (Fig. 1C). Extensive outcrops are on the south side of U.S. 34 and are dominated by black to dark gray psammite to semipelite, with rare phyllite. Beyond the mile 83 road marker to the west, ~1 m thick sills of Big Thompson Canyon tonalite are common (Fig. 2A). Compositional layering in the metasediments, oriented ~110, 66 (right-hand rule) is defined by variations in mica content at the centimeter to decimeter scale and is likely relict bedding ($S_0$). Centimeter to decimeter thick quartz veins are parallel to $S_0$ or cut it at a low angle, and are commonly boudinaged parallel to bedding, indicating flattening strain related to $S_1$ (sub-) parallel to $S_0$. More micaceous phyllitic layers display a crenulation cleavage, regional $S_3$ (see above), oriented ~320, 82 (Fig. 3A). Randomly oriented biotite porphyroblasts up to 2 cm are common and are best seen on bedding parallel fracture surfaces. These porphyroblasts are not aligned with the local foliation, instead appearing to have overgrown the foliation. Curtin (1965) also describes biotite and chlorite poikiloblasts a few kilometers to the north that appear aligned with later generations of crenulation cleavages, and thus are interpreted to have grown during or after their development. This area exposes some of the lowest grade rocks within the Big Thompson Metamorphic Suite and is very near the mapped garnet-in isograd. However, no garnet has been observed by the authors at this location, indicating that the outcrops are in the biotite-zone and just below the garnet-in isograd, or that the bulk compositions were locally not conducive to forming garnet. From here, the trip moves up metamorphic grade with respect to the established isograd patterns (Fig. 1C).

**Stop 2. Viestenz-Smith Mountain Park**
(UTM NAD83 Zone 13T 476285, 4474530)

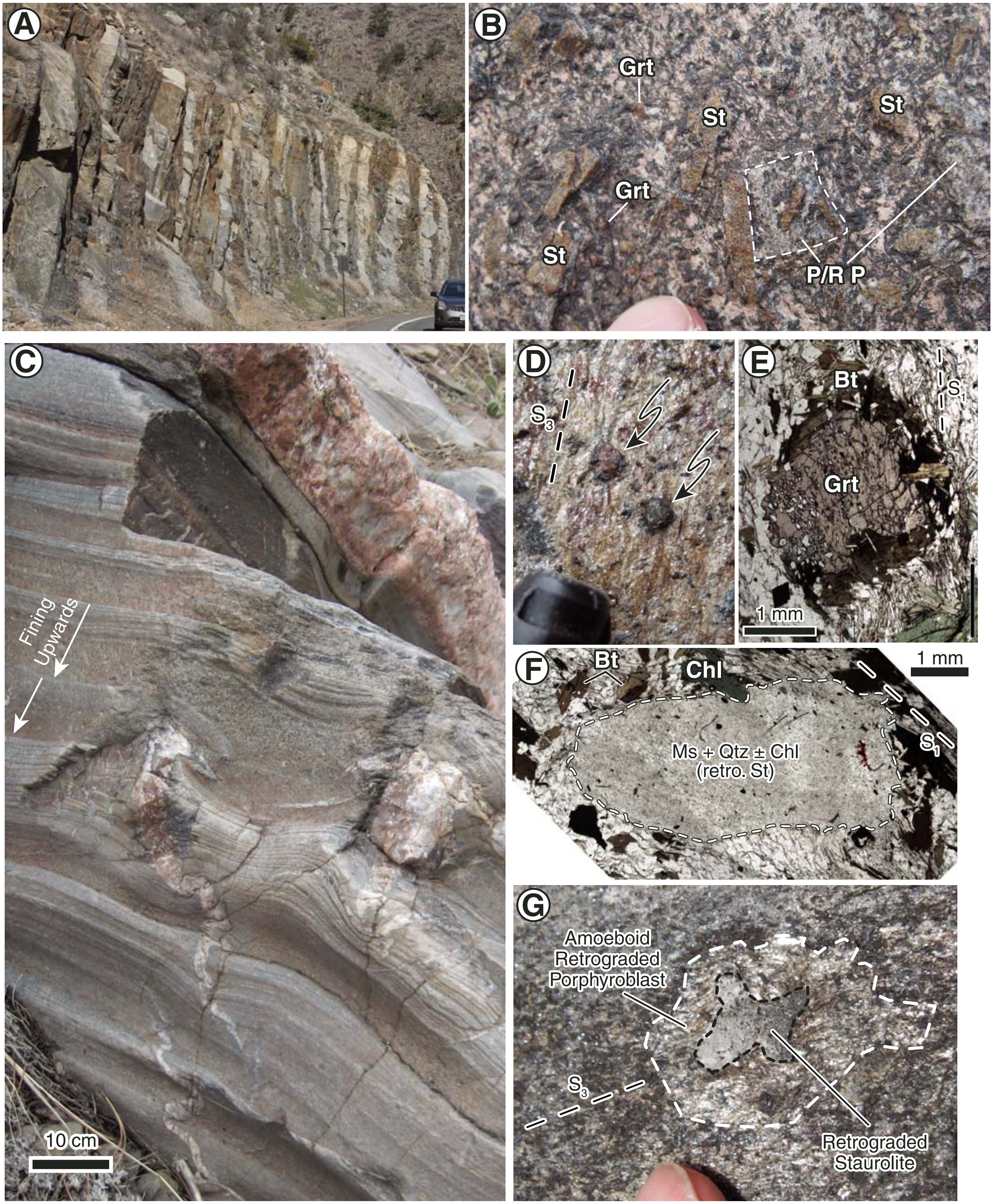
The turnoff for Viestenz-Smith Mountain Park is on the north side of U.S. 34 ~5.8 km (3.6 mi) west of Stop 1 (Fig. 1C). The park, on the south side of the Big Thompson River, is public and provides vault toilets. However, access to the outcrop of interest on the north side of the river across the bridge in the park requires permission of the park's caretaker. Contact information for the caretaker is displayed on the bridge's gate; the authors can provide the contact information for the caretaker upon request. From the park bridge, take the path to the east along the river for ~300 m, then north for ~40 m to the base of a steep slope. Confirmed hazards at this outcrop include falling rock and rattlesnakes.

The rock is predominately interlayered gray psammite and pelitic porphyroblastic mica-schist. Compositional layering occurs on the ~3–10 cm scale and is interpreted to be relict bedding ($S_0$). The dominant tectonic foliation, $S_1$, is parallel to the relict bedding and oriented ~090, 66 but strike varies by ~20 degrees in the area. A weak crenulation, $S_3$, produces an intersection lineation on $S_0$-$S_1$ surfaces and is oriented ~79→165 (Fig. 3A). Porphyroblasts include 1–2 mm black biotite, 1–2 mm red garnet, 1–2 cm yellow-brown euhedral-subhedral staurolite, and one or more generations of pseudomorphs after staurolite (identified by crystal form and twinning) to muscovite+chlorite and/or other retrograded or poikilitic porphyroblasts of unconfirmed identity (Fig. 2B).

This stop is above the andalusite-in isograd, having crossed the staurolite-in isograd approximately halfway between this location and Stop 1. The occurrence of "fresh" staurolite is rare, with the more typical occurrence being muscovite+chlorite pseudomorphs after staurolite. However, in these outcrops, fresh euhedral to subhedral staurolite with very few signs of retrogression can be observed, together with other centimeter-sized porphyroblasts and/or pseudomorphs, possibly staurolite, andalusite or cordierite, some of which enclose the fresh staurolite (Fig. 2B). This stop is very near the location from which Shaw et al. (1999) describe two generations of staurolite. An early-retrograded variety (pseudomorphs) is overgrown by a younger "fresh" variety as seen in this outcrop. The occurrence of several generations of staurolite suggests a multiple-stage growth, which is further supported by the occurrence of garnet rims of distinct composition found elsewhere in the Big Thompson Canyon area (Fig. 4). Although it is theoretically possible for staurolite to have initially grown, have been retrogressed, and then a new generation to have grown in a single P-T loop, $^{40}Ar/^{39}Ar$ thermochronology indicates

→

Figure 2. (A) View to the west of the western portion of the outcrop at Stop 1 beyond the mile 83 road marker. Note the sub-vertical light-colored sills of the Big Thompson Canyon tonalite. (B) Some of the many porphyroblasts on the north side of Viestenz-Smith Mountain Park (Stop 2). Grt—garnet; P/R P—poikiloblasts or porphyroblasts retrograded to muscovite; St—staurolite. (C) Overturned relict bedding with folded quartz tension gashes. Comb-textured alkali-feldspar granite pegmatitic dike in background (Stop 3). (D) Garnet partially and fully retrograded to biotite (arrows) in a $S_0$-$S_1$ surface. Note crenulation cleavage ($S_3$) trending vertically in this image (Stop 3). (E) Photomicrograph of garnet (Grt) partially retrograded to biotite (Bt; Stop 3). (F) Photomicrograph of staurolite (St) porphyroblast retrograded to muscovite (Ms), quartz (Qtz) and chlorite (Chl; Stop 3). (G) Muscovite after staurolite porphyroblast overgrown by an amoeboid retrograded porphyroblast (Stop 3).


A
B
Grt
St
St
Grt
St
P/R P
C
Fining Upwards
10 cm
D
S3
E
Bt
S1
Grt
1 mm
F
Bt
Chl
1 mm
S1
Ms + Qtz ± Chl
(retro. St)
G
Amoeboid
Retrograded
Porphyroblast
S3
Retrograded
Staurolite

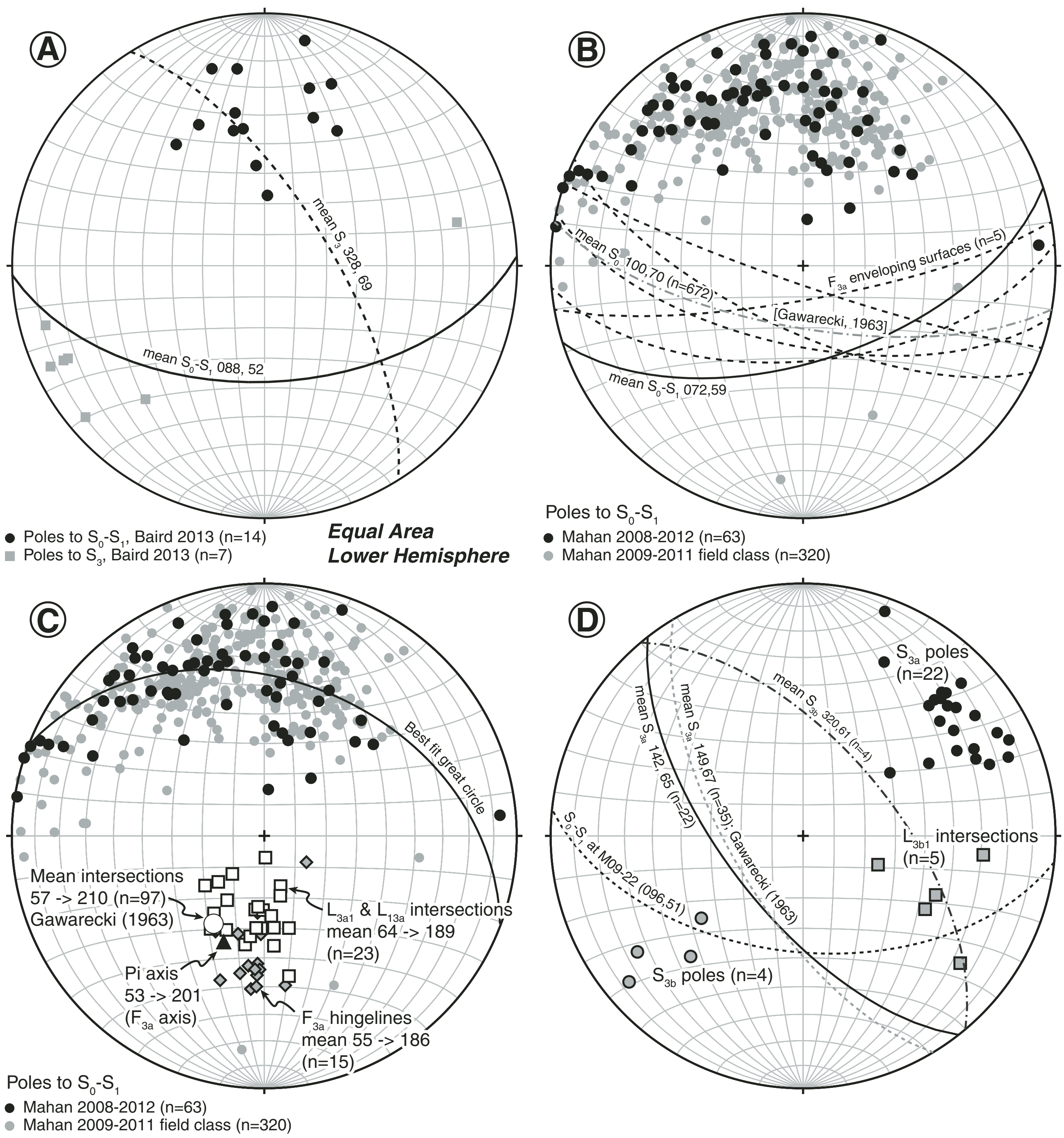



Figure 3. (A) Representative structural data for Stops 1 through 4. (B–D) Summary of structural data for stop 5 at Storm Mountain Drive. See text for detail.

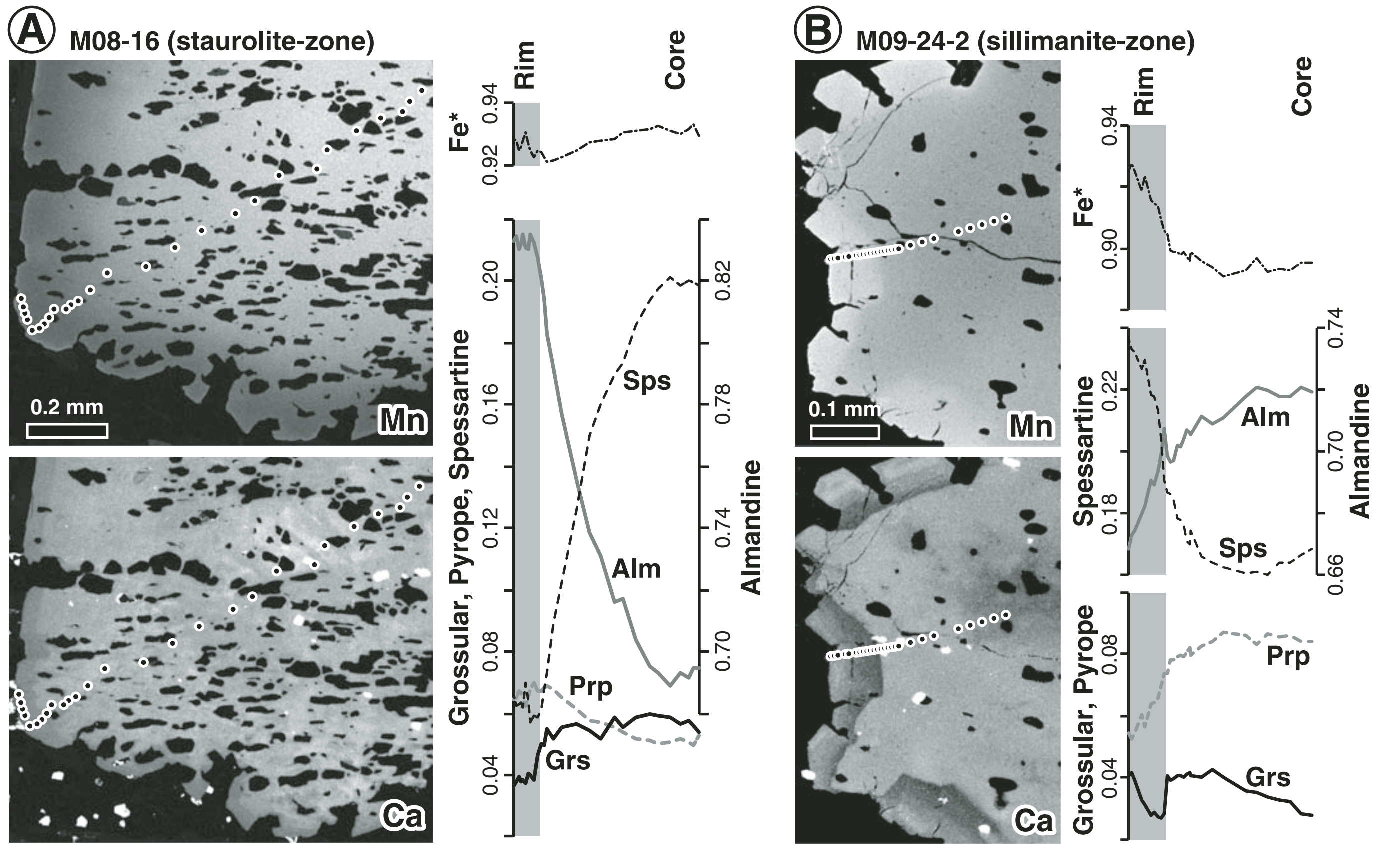



Figure 4. Compositional zoning in garnet porphyroblasts from staurolite- and sillimanite-zone metapelites. Mn and Ca X-ray element maps are accompanied by half-traverses through each grain. In both zoning patterns, a distinct garnet rim is indicated by an abrupt change in grossular content at the grain edge (gray box). (A) Sample M08-16 from the staurolite-zone with a well-preserved prograde zoning defined by a regular decrease in spessartine content and a slight decrease in Fe/Fe+Mg ratio (Fe*). (B) Sample M09-24-2 from the sillimanite-zone depicting strong retrogression defined by a dramatic increase in spessartine content in the rim.

either partial exhumation and cooling followed by reheating of the region to 500–550 °C at ~1.4 Ga, or a protracted residence at elevated temperature below ~450–500 °C (Shaw et al., 1999). Shah and Bell (2011) also argue for multiple periods of staurolite growth, including a late generation at ~1.4 Ga. Thus, the thermal history permits a distinctly younger prograde generation of staurolite. Other minerals that are confirmed elsewhere in the Big Thompson Metamorphic Suite (andalusite, cordierite) also suggest multiple metamorphic events. These will be discussed further at Stops 4 and 5.

**Stop 3. Big Curve**

(UTM NAD83 Zone 13T 475043, 4475303)

About 1.8 km (1.1 mi) west of the Viestenz-Smith Mountain Park access road on U.S. 34 is the "big curve" stop (Fig. 1C). Parking for this stop is on the north side of U.S. 34 and extensive outcrop occurs along the north and east side of the "big curve." The rock is similar to that observed at Stop 2, with $S_0$-$S_1$ oriented ~065, 48. Sharp and gradational contacts between the quartzose and schistose layers within the rock suggest the beds are graded and overturned, younging to the north (Fig. 2C). Quartz tension gashes (10–30 cm long) that are oriented approximately perpendicular to $S_0$-$S_1$ are folded with axial surfaces parallel to $S_0$-$S_1$ (Fig. 2C). The $S_3$ crenulation cleavage, oriented ~335, 75 (Fig. 3A), is subtle but pervasive and is associated with a locally developed mineral lineation. Two sets of igneous rocks occur, decimeter-thick muscovite alkali-feldspar granite (pegmatitic to aplitic) dikes and sills with comb-textures (Fig. 2C) and an ~1 m wide low angle Big Thompson Canyon tonalite dike (found at the apex of the road curve). Both lack the foliation parallel to the relict bedding. The tonalite dike possesses a foliation parallel to $S_3$ and small veinlets at the terminations of the alkali-feldspar granite intrusions are folded by $S_3$. Therefore, they are interpreted to have intruded prior to $S_3$ crenulation cleavage formation. These relationships are similar to those described for "foliated trondhjemite" sills and dikes by Barovich (1986).

Porphyroblasts at this locality are concentrated in the schistose layers and include 1–2 mm black biotite, 1–2 mm garnet (variably retrograded to biotite; Figs. 2D, 2E), 1–2 cm aggregates of fine-grained muscovite pseudomorphs after staurolite (Fig. 2F), and 1–3 cm blocky to ameoboid porphyroblasts of an unconfirmed identity (andalusite?) that could be poikilitic or retrograded to muscovite (Fig. 2G). At least some of the blocky to amoeboid porphyroblasts appear to overgrow the crenulation cleavage.

### Stop 4. Midway

(UTM NAD83 Zone 13T 473444, 4475430)

The Idlewild Dam pull off at Midway on the south side of U.S. 34 is ~1.9 km (1.2 mi) west of the "big curve" stop (Fig. 1C). This location will serve as the lunch stop and has vault toilets. Extensive outcrops on the north side of U.S. 34 extend both west and east from this location for ~1 km. The rocks of focus are a stretch ~200 m to the east of the Idlewild Dam pull off exit (Fig. 5A), though many other interesting features occur at this location.

The metasedimentary rocks here are almost entirely composed of schist that is more homogenous and more strongly deformed than rocks farther east in the canyon. Folded compositional layering, interpreted to be relict bedding, can clearly be observed in one location (Figs. 5B, 5C). Axial planar to the fold is a penetrative $S_1$ schistosity oriented ~081, 46. A crenulation cleavage also is present, oriented ~312, 60, and creates an intersection lineation seen on $S_1$ surfaces. Big Thompson Canyon tonalite bodies are found throughout the area and the easternmost sills in this area are clearly boudinaged parallel to the main $S_1$ schistosity with boudin axes gently plunging to the west (Fig. 5A). On the margin of some of the tonalite sills is a ~10-cm-thick border of nearly pure polycrystalline tourmaline. Also observed within the tonalite are quartz tension gashes perpendicular to the sills that are folded with axial surfaces parallel to the main schistosity. Large porphyroblasts occur only in select locations and include 20+ cm long, biotite rimmed andalusite and muscovite+chlorite pseudomorphs after staurolite (Figs. 5D, 5E).

The structural relationships at this location potentially provide temporal constraints on the formation of the main $S_1$ fabric. Figure 5B shows what is interpreted as a rare $F_1$ fold of $S_0$. Cutting across this fold is a small, nearly planar centimeter-scale dike that appears to be related to the Big Thompson Canyon tonalite, which in turn contains the $S_3$ fabric. A similar relationship between $S_1$, tonalite, and $S_3$ is observed at Stop 3. However, the boudinage of the tonalite sills in the plane of $S_1$ suggests pre- or syn-kinematic intrusion of at least some of the tonalite with respect to $S_1$. Collectively these observations suggest the Big Thompson Canyon tonalite is syn-kinematic and the 1726 ± 15 Ma intrusive age of the Palisade tonalite (Barovich, 1986) would constrain $S_1$ fabric development to that time. An alternative view of these outcrop relationships could be that the planar fabric hosting the boudinaged tonalite is actually an $S_2$ fabric. As stated earlier, Barovich (1986) concluded from fabric studies around the Palisade intrusion (visible as cliffs high above the canyon to the north) that the tonalite post-dates both $S_1$ and $S_2$ based on the interpretation that the intrusion locally re-oriented these earlier fabrics during its "forceful emplacement." All of these possibilities should make for interesting discussion at this stop.

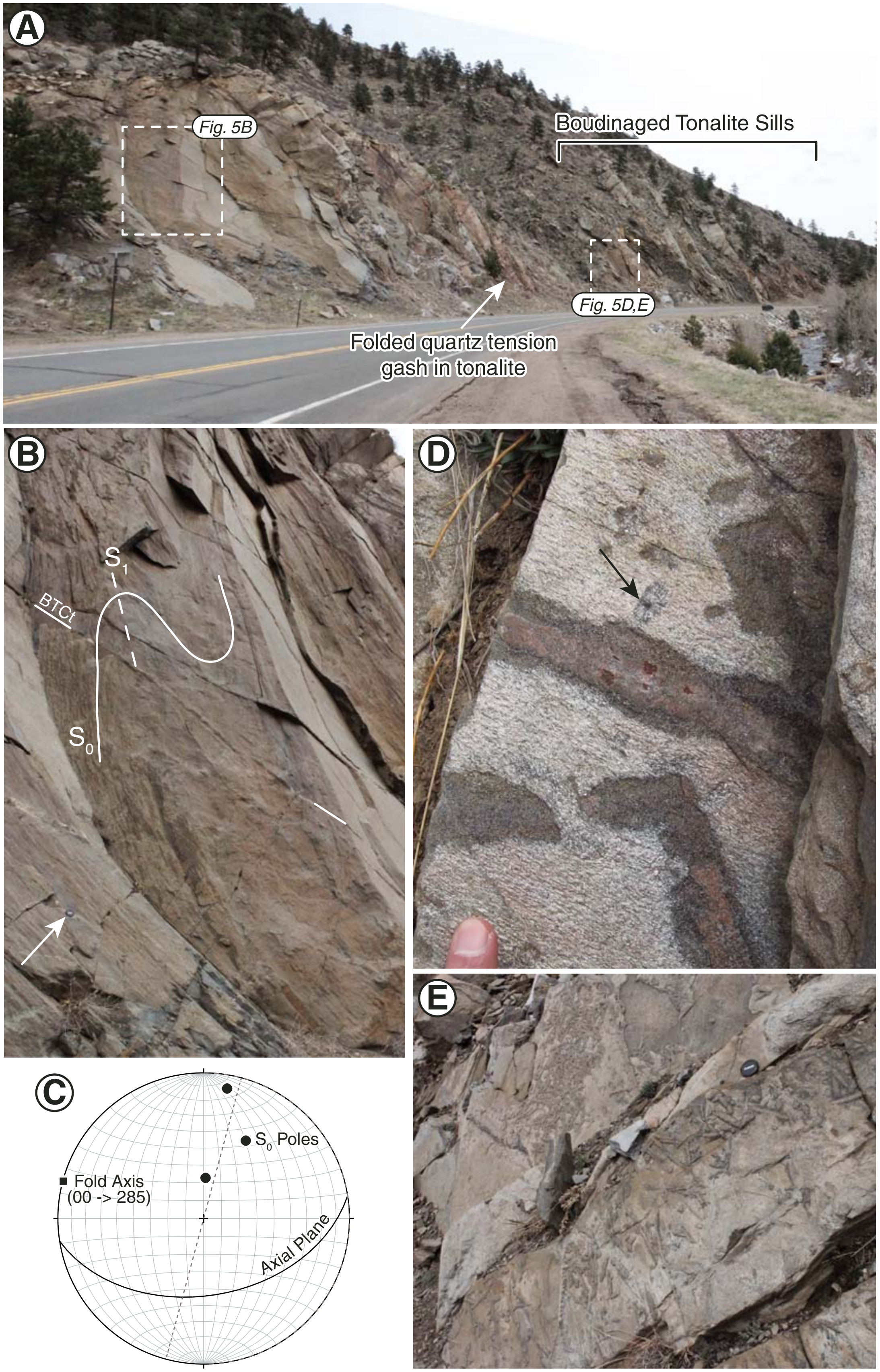
### Stop 5. Storm Mountain Drive

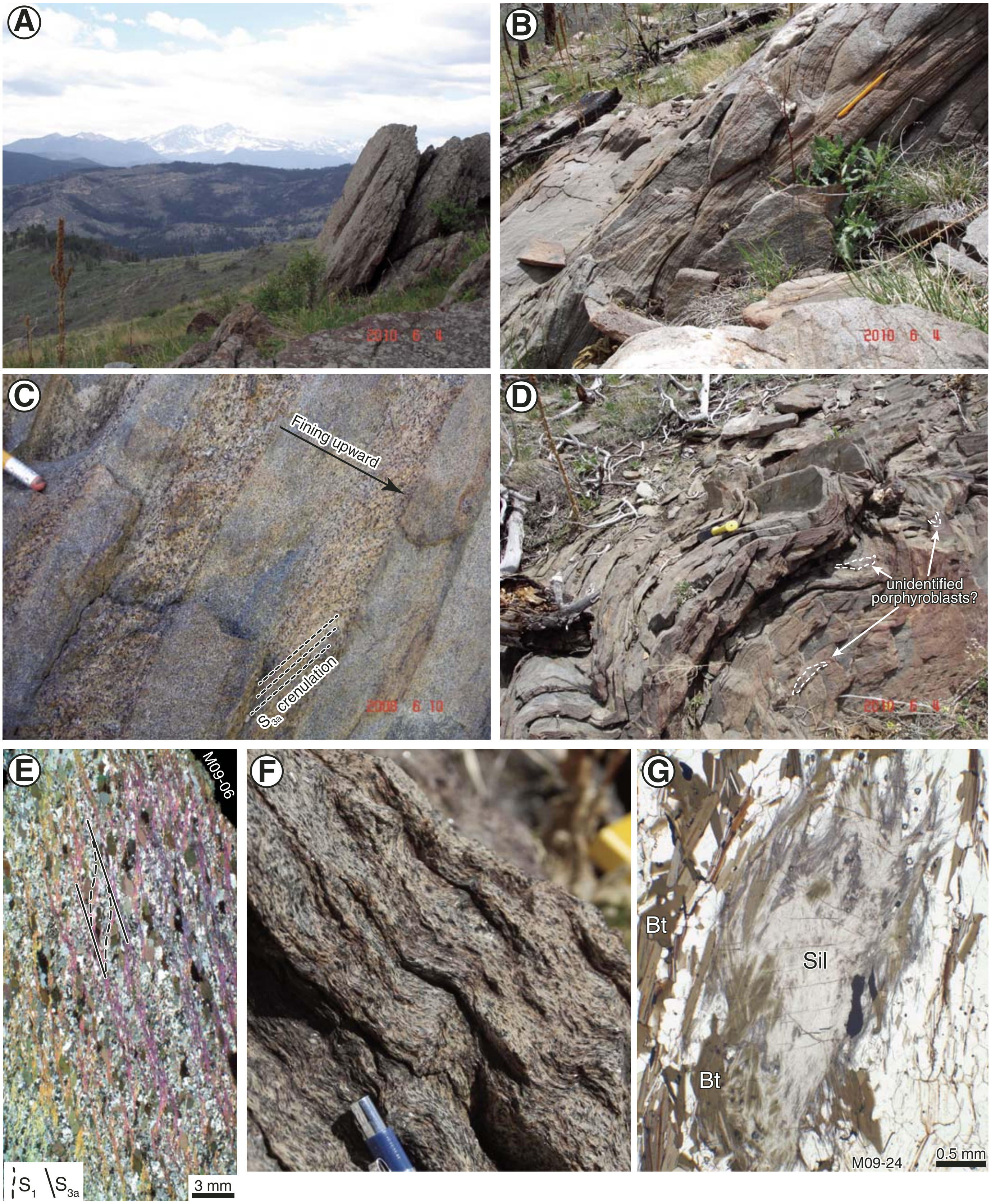
(UTM NAD83 Zone 13T 470555, 4478710)

Continue west along U.S. 34 until Drake (2.7 km, 1.7 mi) and turn right (northwest) onto County Road 43. After 320 m (0.2 mi), turn right onto Storm Mountain Drive (dirt road). Go 3.5 km (2.2 mi) and turn left at a T-intersection continuing on Storm Mountain Drive. Stay left on Storm Mountain Drive at a Y-intersection after 320 m (0.2 mi). Stay left again at another Y-intersection after 1.6 km (1.0 mi). At this point, one has crossed into an old wildfire zone where outcrop exposures are excellent. After another 1.3 km (0.8 mi), there is a large pullout on the left just before the road starts to curve around right again, this is Stop 5 (Fig. 1C). Elevation here is ~8000 feet and good views of the high peaks in Rocky Mountain National Park can be seen to the southwest (Fig. 6A). The focus of this stop is a series of outcrops in a roughly 100 × 180 × 180 m triangle downhill to the east and south from the pull out. However, outcrops are generally abundant here and those by the pullout contain many of the same features as those down the hill. The hillside is somewhat steep and rocky and there are numerous downed tree trunks left over from the fire, so be careful.

The majority of the rocks are layered porphyroblastic garnet-biotite-muscovite-andalusite ± sillimanite ± cordierite schist and micaceous quartzite. At least one outcrop in the "triangle" contains sandy lenses with possible cross-bedding preserved, indicating that the relict bedding is overturned (Fig. 6B). More commonly preserved are textures consistent with graded beds that also indicate an overturned stratigraphic relationship (Fig. 6C). Relict bedding and a penetrative $S_1$ cleavage in this general area strikes roughly 072, 59, but open to tight, moderately steeply plunging $F_{3a}$ folds result in variable strikes at the kilometer- and outcrop scales (Figs. 3B–3D; 6D). At least two generations of crenulation cleavage can be observed in the more schistose outcrops with associated intersection lineations (Figs. 3B–3D; 6E, 6F). The first two generations of structures ($S_1$ and $S_{3a}/F_{3a}$) are consistent with much of the structure described by Gawarecki (1963) from the region just east of Cedar Park (Figs. 3B, 3C, 3D). However, there is also an incipient but distinctly younger generation of centimeter-scale spaced crenulation cleavage ($S_{3b}$) locally

Figure 5. (A) Features of interest at Stop 4, located 200 m east of the Idlewild Dam pull off, view to the east. (B) Fold in $S_0$ with $S_1$ axial planar to the fold. "BTCt" is a small dike related to the Big Thompson Canyon tonalite, which appears undeformed by $D_1$, but contains an $S_3$ foliation (not observable in the image). Lens cap for scale (arrow). (C) Stereonet of salient data from fold displayed in B. (D) Large biotite rimmed andalusite and retrograded porphyroblast with weathered out core (arrow). (E) Fabric parallel surfaces of micaschist with abundant retrograded porphyroblasts (staurolite?) and/or poikilitic porphyroblasts.


A
Fig. 5B
Boudinaged Tonalite Sills
Fig. 5D,E
Folded quartz tension
gash in tonalite
B
$S_1$
BTCt
$S_0$
D
E
C
$S_0$ Poles
Fold Axis
(00 -> 285)
Axial Plane


A
2010 6 4
B
2010 6 4
C
Fining upward
$S_{3a}$ crenulation
2008 6 10
D
unidentified
porphyroblasts?
2010 6 4
E
M09-06
$S_1$ $S_{3a}$
3 mm
F
G
Bt
Sil
Bt
M09-24
0.5 mm

developed. Whereas the well-developed generation ($S_{3a}$) consistently strikes SE and dips SW (mean 142, 65), $S_{3b}$ consistently strikes NW and dips NE (mean 320, 61; Fig. 3D). Furthermore, distinct intersection lineations on the $S_0$-$S_1$ composite surface can be observed associated with $S_{3a}$ and $S_{3b}$, and the latter deflects the former. $S_{3b}$ is geometrically similar to the prominent $S_3$ crenulation cleavage observed in previous stops in the canyon, and is the basis for the choice of a secondary b-notation. Barovich's (1986) $S_3$ cleavage data collected around Palisade Mountain has similar strike but dips both NE and SW, suggesting that the data set may be a mixture of the two cleavages.

Many of the outcrop lithologies are also characteristically "lumpy" with numerous muscovite-pseudomorphs (after staurolite or possibly andalusite) and others are composed of fresh poikilitic andalusite. These rocks are also near the sillimanite-in isograd and millimeter- to centimeter-sized pods of sillimanite occur locally (Fig. 6G), most commonly in more quartz-rich layers. Cordierite has also been observed by the present authors in at least one thin section from this area, but very little can be said at present regarding its relationship to fabrics or other major metamorphic phases. One additional porphyroblastic phase occurs locally in micaceous layers in outcrops that are otherwise dominantly quartzite. These bluish-gray porphyroblasts are large and oblate in the $S_0$-$S_1$ surface (up to 10 cm long), inclusion-rich and commonly occur wrapping around $F_{3a}$ folds (Fig. 6D) but appear also appear to overgrow the $S_{3a}$ crenulation cleavage. Their identity has not yet been confirmed.

**Stop 6. Glen Haven**
(UTM NAD83 Zone 13T 462609, 4478285)

Return to County Road 43, turn right and head northwest toward Glen Haven for ~11.0 km (7.0 mi), where there is a large pullout on the south side of the road. Biotite migmatite, mixed with K-feldspar, sillimanite, biotite, ± muscovite and tourmaline, crops out on the south side of the pullout (Fig. 1C). Leucosome is typically 1–3 cm thick (Figs. 7A, 7B, 7C), and can either be parallel to the main schistosity or crosscut it (Fig. 7C). Leucosome is locally haloed by a biotite "selvage" (Figs. 7B, 7C). The compositional layering is oriented 020, 54 and is crosscut by an $S_3$ (?) crenulation oriented 295, 68.

Figure 6. (A) Southwestern view on some of the Rocky Mountain high peaks from Storm Mountain Drive (Stop 5). (B) Preserved cross-bedding and (C) graded-bedding indicating an overturned sequence. (D) Open to tight $F_{3a}$ folds with unidentified porphyroblasts in the lower part of the outcrop (possibly andalusite or cordierite?). (E) Thin section view of crenulation cleavage with development of the $S_{3a}$ schistosity. (F) Same crenulation as viewed on the outcrop. (G) Millimeter-sized nodule of sillimanite (Sil), typically growing in close relation with mica (biotite [Bt] especially), suggesting a sillimanite-in reaction by reaction with mica. At the outcrop scale, whitish sillimanite pods stand out of the outcrop due to hardness contrast with mica.

Scattered throughout the rock are centimeter-sized nodules of fibrolitic sillimanite (Figs. 7D, 7E). Cordierite has also been reported in the area (e.g., Punongbayan, 1972; Cole, 1977; Cole and Braddock, 2009). In this case, cordierite is a prograde mineral, whereas it may be considered as a retrograde phase in lower grade areas of the Big Thompson Metamorphic Suite. Muscovite has two distinct textures here. The obvious 1–2 cm randomly oriented porphyroblastic muscovite in more pelitic areas is interpreted to be retrograde in nature (Nesse, 1984). Prograde muscovite can only be confidently identified in thin section (Fig. 7E) where optically continuous fragments of muscovite are dissected and/or partially replaced by biotite, quartz, and/or sillimanite. This texture suggests that melting in these rocks was facilitated via a muscovite-dehydration melting reaction, which is classically recognized as (cf. Nesse, 1984):

Muscovite + Quartz = K-feldspar + Sillimanite + melt.

This reaction would additionally induce the growth of a second sillimanite generation, the first generation being produced by polymorphic reaction from andalusite. In other parts of the Big Thompson Metamorphic Suite, muscovite is lost from the assemblage (above the K-feldspar-in isograd) prior to the onset of melting. However, large retrograde muscovite flakes related to hydration following crystallization of the melt occur locally. In addition, migmatitic sillimanite-biotite bearing rocks above the melt-in isograd in the Estes Park and Pingree Park areas commonly contain cordierite, with or without garnet (Cole and Braddock, 2009), suggesting that melting was facilitated in these rock compositions via the (vapor-absent) biotite-dehydration melting reaction:

Biotite + Sillimanite + Quartz = Cordierite + Garnet +
K-feldspar + melt.

This latter assemblage and inferred reaction suggests that rocks were relatively water-undersaturated during the higher-T segments of this P-T path compared with the former assemblage and melting reaction, and reached up to and possibly exceeded 700 °C. As discussed in Nesse (1984), the map pattern of leucosome-bearing rocks in the upper parts of Big Thompson Canyon does not suggest they formed through injection of felsic veins during the region's extensive magmatic activity, but through in situ melting of the metasediments.

## DISCUSSION

Despite previous efforts to elucidate the tectonometamorphic history of the Big Thompson Metamorphic Suite, a compilation of existing mapping, structural and petrographic work suggests that a number of uncertainties remain. Acknowledging the superficial simplicity of the isograd "sequence" as a basis for interpretation of a major part of the thermal evolution of the Big Thompson Metamorphic Suite, the evidence

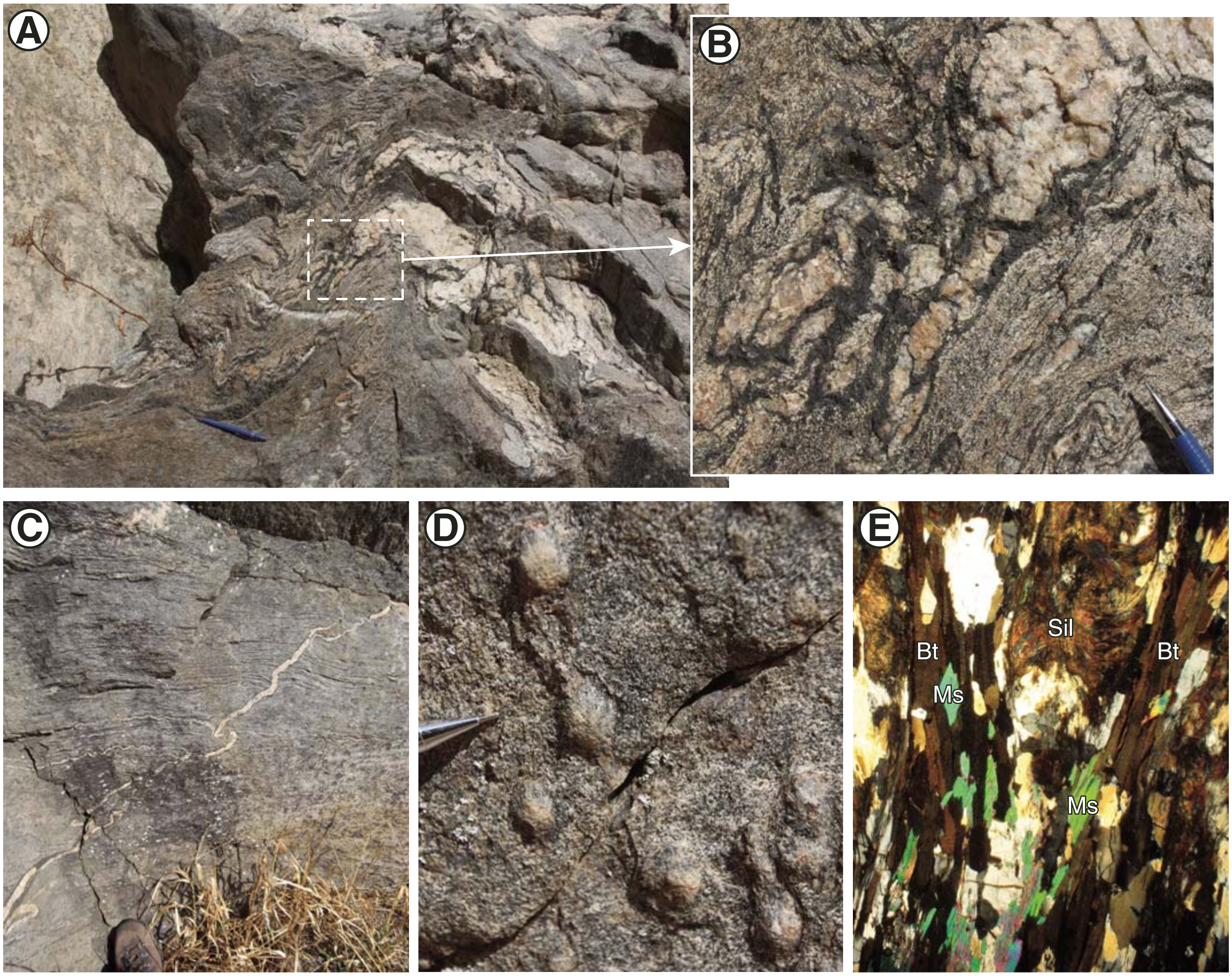



Figure 7. (A) Migmatitic biotite schist at Stop 6 with leucosome (sub-)parallel to the main foliation. (B) Close-up view of A) highlighting the biotite selvage around the leucosome. (C) Leucosome cross-cutting the foliation. (D) Sillimanite nodule. (E) Photomicrograph of sillimanite (Sil) nodule with biotite (Bt), quartz and K-feldspar. Although rare, relic of muscovite (Ms) is locally observed. Field of view is 4.4 mm.

supports overprinting of multiple generations of key indicator minerals. More than one scenario for the P-T evolution can explain second generation minerals (Fig. 8): (*a*) two distinct heating-cooling cycles (two P-T loops), (*b*) one or more retrograde events, or (*c*) a second heating event associated with the same orogenic cycle (that is, within a single P-T loop). Monazite ages associated with multiple generations of foliation intersection axes (Shah and Bell, 2012) indicate that multiple fabric-forming events were associated with Yavapai-age thermal events. However, ~1.4 Ga $^{40}$Ar-$^{39}$Ar mica ages (Shaw et al., 1999) and ages from monazite inclusions in andalusite and cordierite porphyroblasts (Shah and Bell, 2012) provide valid cause to invoke a second thermal event at this time, likely linked to more established events in southern Colorado and northern New Mexico (Picuris Orogeny; Daniel, 2012) and regional plutonism throughout the southwest (e.g., Silver et al., 1977; Anderson, 1983).

Exact constraints on the P-T conditions achieved and P-T-t-D relationships during single or multiple events are also still subject to debate. Based on existing data and the textural relationships described above, three scenarios could be suggested to describe the P-T-t history of the Big Thompson Metamorphic Suite (Fig. 8). Figure 8A presents a case for a single P-T loop, where different parts of the Big Thompson Metamorphic Suite evolved along a low-pressure trajectory (constrained by the absence of kyanite), reaching peak conditions of ~650 °C in the sillimanite+ K-feldspar zones (Nesse, 1984) and T >700 °C in the migmatite zone (Cole, 1977; Munn and Tracy, 1992; Munn et al., 1993). However, this scenario fails to explain the multiple generations of key minerals, notably the occurrence of multiple generations

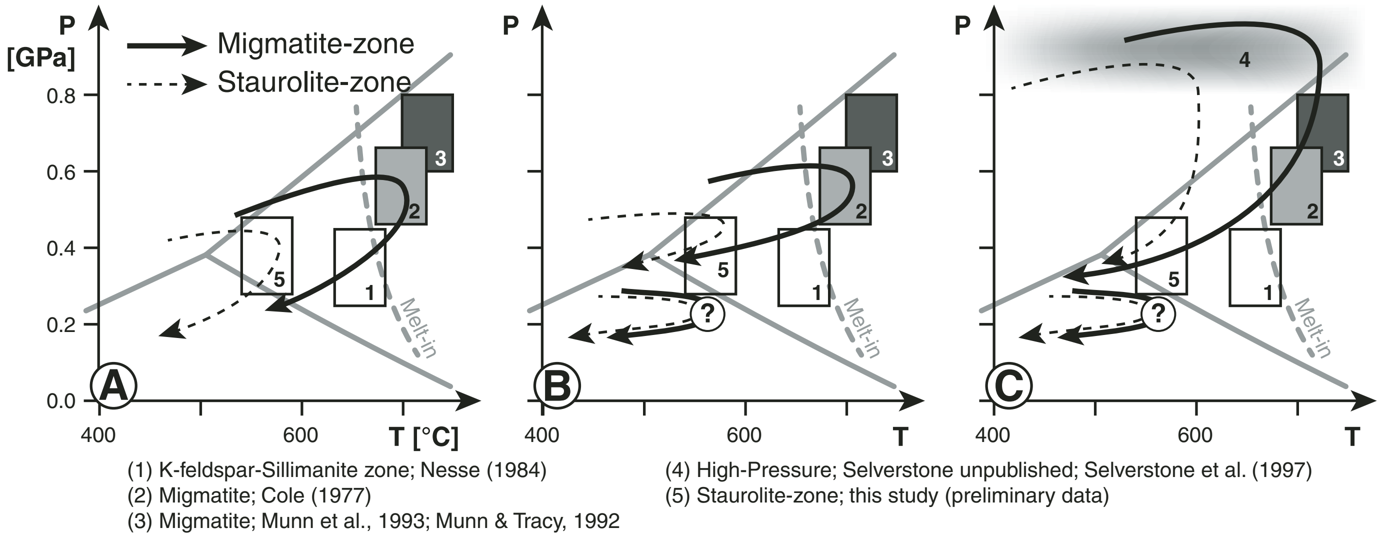



Figure 8. Possible PT-paths for rocks from Big Thompson Canyon. See text for discussion.

of staurolite (Shaw et al., 1999; Shah and Bell, 2011), the mineral sequence andalusite > sillimanite > andalusite observed by Punongbayan (1972), and the obvious two-stage growth of garnet (Fig. 4). A second scenario involving two separate P-T loops (Fig. 8B) can be invoked to explain these observations. Here, a first event evolved along a path similar to that described in Figure 8A. Presumably occurring at ~1.7 Ga, this event would bring rocks from the middle and western Big Thompson Metamorphic Suite to around 500 °C, 0.4 GPa and 700 °C, 0.6 GPa, respectively. A second P-T loop could explain the generation of andalusite, staurolite and cordierite along a low-P trajectory that reached peaks of ~500 °C across the area. Modeling of the partial resetting of $^{40}Ar$-$^{39}Ar$ hornblende ages by Shaw et al. (1999) suggests that the heating event that reset $^{40}Ar$-$^{39}Ar$ mica ages at ~1.4 Ga reached up to a maximum of 550–600 °C and for only a short period of time. If this age does represent the timing of secondary porphyroblast growth, then the Big Thompson Metamorphic Suite experienced a relatively long period of crustal residency (200–300 m.y.) between the original thermal cycle and a second re-heating event.

Whereas temperature constraints for these metamorphic events appear relatively well defined, the question of maximum pressure during the first and second P-T cycles remains open. Selverstone et al. (2000) suggested that maximum pressures reached 0.8–1.0 GPa during metamorphism of the Big Thompson Metamorphic Suite, an estimate based on inclusions of plagioclase in garnet. In contrast, most authors (Cole, 1977; Nesse, 1984; Munn and Tracy, 1992; Munn et al., 1993) suggest that rocks were metamorphosed at lower pressures (~0.4–0.7 GPa), which is more consistent with the absence of high-P mineral phases (e.g., kyanite) and the early loss of most muscovite before migmatization. Therefore, a third scenario could be considered (Fig. 8C) where early stages of metamorphism evolved at higher pressures (up to 1.0 GPa) prior to decompression. However, this may require the second event to be the cause of mineral assemblage zoning in the Big Thompson Metamorphic Suite. The distinctions between these alternative P-T-t-D histories have significant implications for the degree of crustal thickening involved and thus for the role of the Big Thompson Metamorphic Suite in the tectonic history of northern Colorado.

Temporal relationships between metamorphic episodes and deformation events also remain unclear. Linking all the above to orogenic events is necessary to build a complete tectonic picture of the role the northern Colorado Front Range rocks play in the Proterozoic assembly of North America. The structural relationships between the ~1.7 Ga Big Thompson Canyon tonalite and the main recognized fabrics indicate that those deformation episodes and the earliest thermal events in the area can generally be attributed to the Yavapai Orogeny (or Boulder Creek Orogeny of Sims and Stein, 2003). However, more precise constraints on the timing of the multiple deformation events are needed to better understand the tectonic record. For example, is there an unrecognized extensional deformation episode related to formation of the Poudre basin of Dewitt et al. (2010)? Or do all of the Paleoproterozoic deformation events recorded by the Big Thompson Metamorphic Suite reflect a complex history of arc accretion involving multiple NW- and NE-directed subduction systems (Jessup et al., 2005)? Was there also deformation associated with ~1.4 Ga thermal and metamorphic overprinting? If so, what is its relationship to other localized domains of ~1.4 Ga strain in northern Colorado such as the Moose Mountain shear zone, other major Mesoproterozoic shear zones in Colorado (e.g., Shaw et al., 2001; Allen, 2005; Shaw and Allen, 2007; Allen and Shaw, 2011) or to more regional orogenic activity such as the Picuris Orogeny recently recognized in northern New Mexico (Daniel et al., 2013, this volume)? Since the earliest research on the Big

Thompson Metamorphic Suite, a wide variety of new petrologic, geochemical, and geochronological techniques have been developed that are well suited to solving the outstanding issues regarding the Big Thompson Metamorphic Suite and surrounding areas.

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