FIELD GUIDE TO CARBONATE MYLONITES AND REACTIVATED BASEMENT FAULTS OF THE LEADORE AREA

Stuart D. Parker[1] **and David M. Pearson**[2]

[1]*Montana Bureau of Mines and Geology, Butte, Montana*
[2]*Idaho State University, Pocatello, Idaho*

INTRODUCTION

Situated in the central Beaverhead Mountains, south of the Idaho–Montana border, the northern part of the 1:24,000-scale Leadore quadrangle hosts complicated contractional and extensional structures that highlight a long history of persistent basement and stratigraphic weaknesses within the interior of the North American Cordillera (figs. 1, 2). Early stage carbonate mylonites define shear zones that follow thin lithologic horizons above a regional unconformity, which we interpret to have formed during a phase of Cretaceous thrusting that was characterized by a thin-skinned structural style. In contrast, Mesoproterozoic to Ordovician quartzites and plutonic rocks of the Lemhi arch basement high were carried by brittle thrusts that cut across lithologic boundaries at moderate to high angles; these thrusts are characteristic of a thick-skinned structural style,

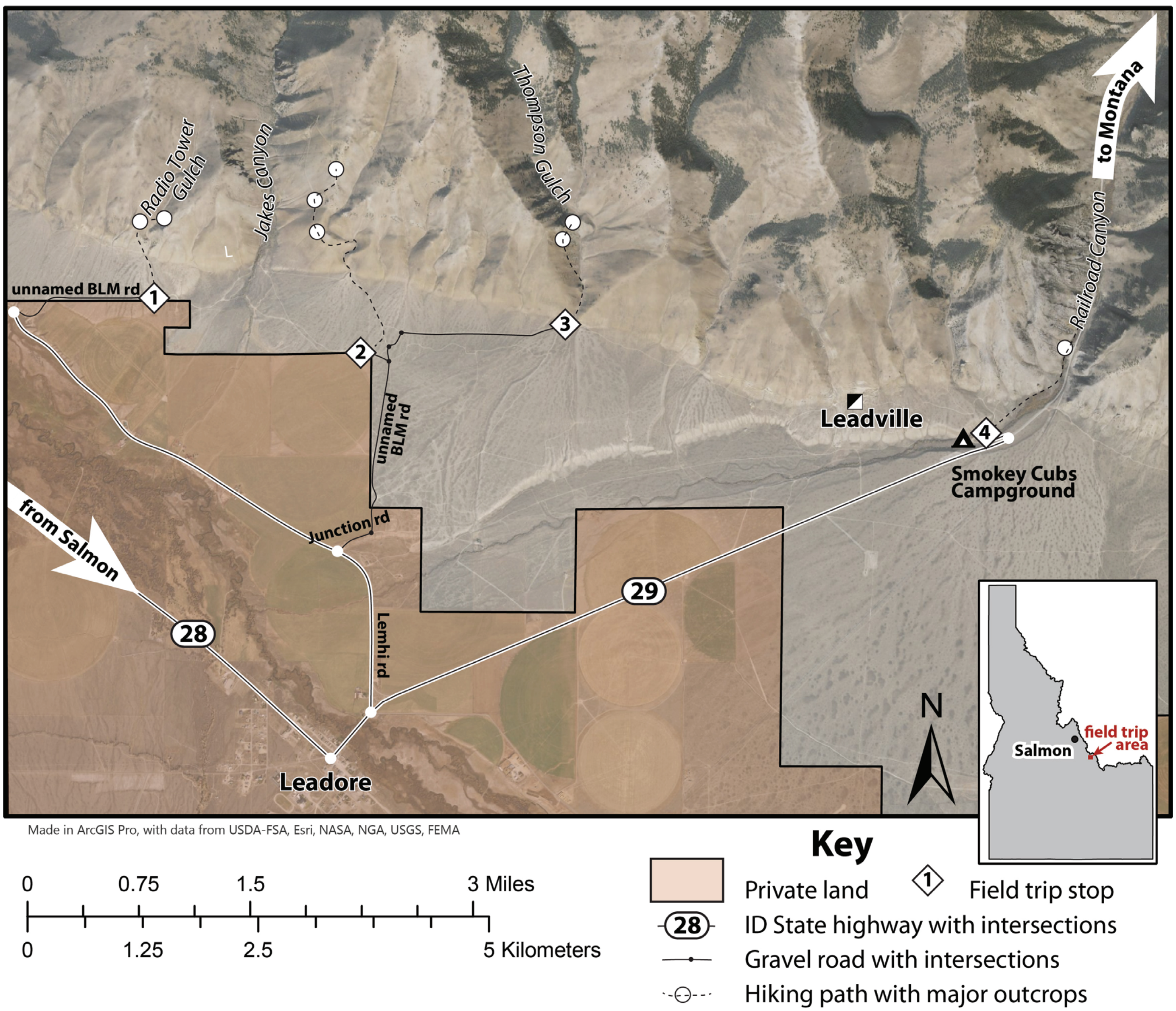

Figure 1. Map showing field trip stops and outcrops described in this field guide. The inset map shows location in relation to Salmon, Idaho. Note that road names may be incorrect on mapping applications.

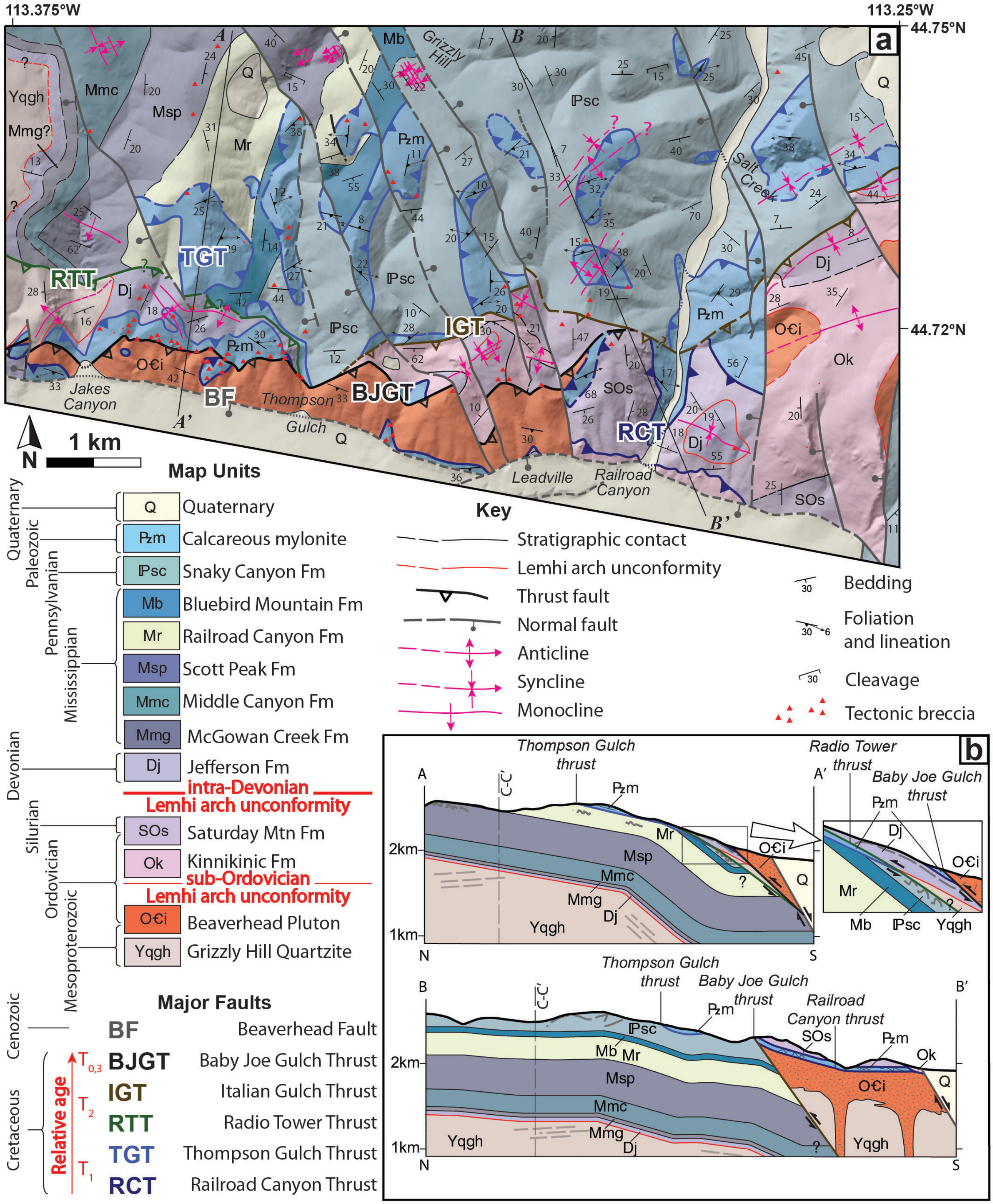

Figure 2. Simplified geologic map of the northern part of the Leadore quadrangle and cross sections, modified from Parker and Pearson (2021). See Parker and Pearson (2020) for detailed 1:24,000-scale map. Abbreviated unit names are used on subsequent figures.

and truncate the older carbonate mylonites. We interpret that burial heating during thrusting and foreland basin sedimentation resulted in elevated temperatures that accentuated the strength contrast between weak carbonate rocks that deformed plastically, and structurally lower, mechanically strong quartzites and igneous rocks that deformed brittlely. This strength contrast not only localized early thin-skinned deformation to within mechanically weak carbonates at the bottom of the regionally continuous middle Paleozoic passive margin succession above the Lemhi arch, but also resulted in a bewildering variety of outcrop-scale structures that make the region an excellent field trip locality.

In this field guide we will highlight the numerous stratigraphic and structural weaknesses that coincide with later thrust fault detachments, near the basement/cover rock contact of the Lemhi arch. We hope to convince participants that overlapping thin- and thick-skinned structural styles are not confined to the foreland of southwestern Montana, but instead occur throughout the Idaho–Montana fold-thrust belt, particularly where sedimentary rocks drape the underlying basement.

GEOLOGIC BACKGROUND

The North American Cordillera is a type example of an ancient orogenic belt formed during ocean–continent convergence. Horizontal shortening in the Idaho–Montana fold-thrust belt occurred mostly in the Cretaceous, from ca. 135 to 55 Ma (e.g., Yonkee and Weil, 2015). Weak, layered sedimentary rocks of the continental passive margin deformed mostly as imbricated thrust sheets bounded by a series of décollements and low-angle-to-bedding thrusts that cut up stratigraphy in the direction of transportation. This structural style is often described as "thin-skinned," although individual thrust sheets may be kilometers thick. Stronger, more massive metasedimentary and igneous rocks of the underlying basement deformed mostly as broad uplifts, with mid-crustal detachments linked to high-angle thrusts or reverse faults that cut indiscriminately through the upper crust. This structural style is often described as "thick-skinned." The Idaho–Montana fold-thrust belt contains a broad "overlap zone" of both thin- and thick-skinned thrusts, which in recent years has been central to debates regarding the role of flat-slab subduction in the Sevier–Laramide orogeny (e.g., Garber and others, 2020; Orme, 2020). Recent work in the Leadore quadrangle (Parker and Pearson, 2020, 2021) has suggested that the overlap zone between thin- and thick-skinned thrusts spans most of the Idaho–Montana fold-thrust belt. Within the northern part of the Leadore quadrangle, we can see exposures of the lower structural levels of the Idaho–Montana fold-thrust belt, allowing us to investigate the role that stratigraphic and structural weaknesses play in determining structural style.

STRATIGRAPHY

The stratigraphy of the field trip area lies near the hinge line of the Laurentian passive margin, separating thin sedimentary cover rocks atop the craton to the east (Montana) from thicker strata deposited on extended crust of the rift-passive margin to the west (Idaho). In the Leadore quadrangle (fig. 2), a ~2-km-thick (6,500 ft) section of Devonian to Pennsylvanian carbonate and siliciclastic rocks rests in angular unconformity on fine-grained Mesoproterozoic (?) quartzite (Lonn and others, 2019; Parker and Pearson, 2021). This intra-Devonian Lemhi arch unconformity (fig. 2; Sloss, 1954; Scholten, 1957) defines a basement high that is interpreted as a horst within the rift margin (e.g., Link and others, 2017). The Devonian Jefferson Formation records flooding of the Lemhi arch, which remained a topographic high during deposition of the early passive margin (e.g., Ruppel, 1986). This thin, discontinuous stratigraphic section of the hinge line occurs throughout much of the Beaverhead and Tendoy Mountains (fig. 3).

A thicker, more complete stratigraphic section lies to the south, in fault contact with the condensed section described above (fig. 3). The ca. 500 Ma Beaverhead pluton intruded into the tilted Mesoproterozoic quartzites (fig. 2) that locally make up the sub-Ordovician Lemhi arch unconformity (e.g., Scholten and Ramspott, 1968; Link and others, 2017). This is overlain by the well-cemented Ordovician Kinnikinic Quartzite and a thick section of Silurian to Devonian reef-bearing dolostones. In contrast to the Devonian section that flooded the Lemhi arch, this section is much thicker, older, continuous, and was deposited in deeper water. Exposures in the neighboring Lemhi Range, only about 17 km (11 mi) away, are characteristic of much of east-central Idaho and suggest that the total passive margin section was about twice as thick as the corresponding section in the Beaverhead Range (fig. 3). Within the northern Leadore quadrangle, these contrasts in thickness, completeness, and depositional environment pinpoint the fault-bounded hinge line of the Lemhi arch near its highest point (fig. 3).

STRUCTURE

Shortening during the Cretaceous juxtaposed these two segments of the Lemhi arch, resulting in the complicated structures visible today (fig. 2). The local stratigraphic thickness of a few kilometers is comparable to those found throughout the foreland of southwestern Montana, where deformation is entirely brittle. However, carbonates of the Leadore quadrangle deformed plastically, forming impressive carbonate mylonites that indicate higher temperatures during deformation (fig. 4). Maximum temperature estimates of around 280°C (±25) for the Devonian Jefferson Formation suggest that the apex of the Lemhi arch was buried to at least about 6.5 km (~21,000 ft) during the Cretaceous (Parker and others, 2022). This is part of a regional

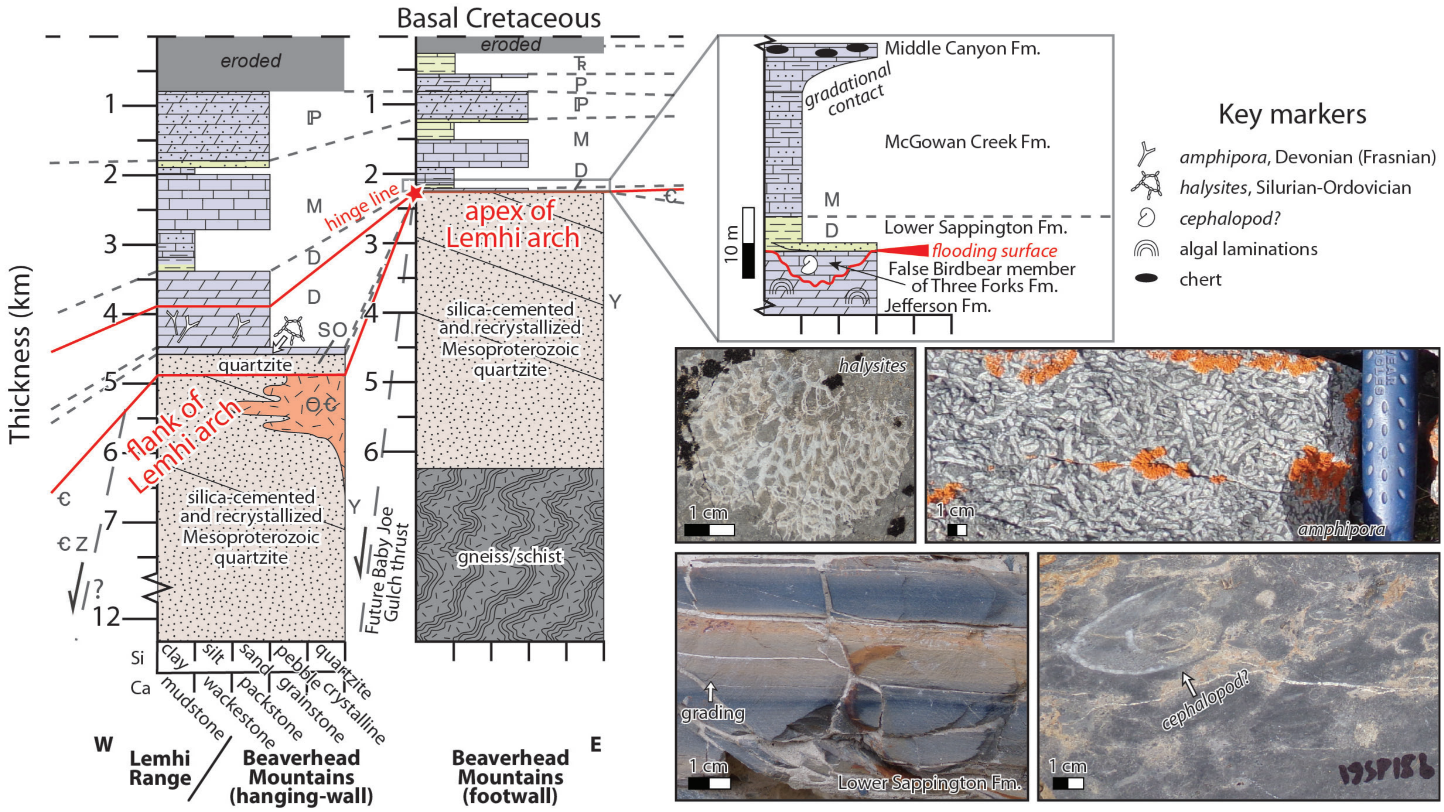

Figure 3. Simplified stratigraphic columns and key markers of the Leadore area, modified from Parker and Pearson (2021). Predominantly siliciclastic units shown in yellow-green; carbonate units shown in purple. General unit correlations and relative age shown by dashed lines, with Lemhi arch unconformities shown in red. Inset shows detailed Devonian to Mississippian stratigraphy (see Grader and others, 2016). Note the abrupt thickness and stratigraphic changes across the hinge line, and the pre-Devonian normal fault we interpret was later reactivated as the Baby Joe Gulch thrust.

temperature trend, interpreted as widespread syntectonic burial during initial shortening and wedge-top deposition in the Idaho–Montana fold-thrust belt (ca. 135–80 Ma; Parker and others, 2022).

Among the oldest fold-thrust structures are carbonate mylonites of the Thompson Gulch and Railroad Canyon thrusts, which structurally overlie a continuous section of the Lemhi arch (Lonn and others, 2019). The low-angle fault contact shallowly cuts upsection toward the east. The fault trace connects to the regional-scale Fritz Creek thrust and its imbricates (Pass Peak and Dry Canyon thrusts of Lucchitta, 1966; Skipp, 1988). This regional detachment generally parallels the Devonian flooding surface above the Lemhi arch and served as the décollement to the early Idaho–Montana fold-thrust belt (Hait, 1965; Beutner, 1968; Parker and Pearson, 2021). Sub-horizontal east–west-stretching lineations and kinematic indicators give a top-to-the-east sense of shear for this thin-skinned thrust system (fig. 5a).

The Radio Tower and Italian Gulch thrusts cut the mylonite (fig. 2), demonstrating that they are younger (Parker and Pearson, 2020). These later thrusts cut across bedding of well-cemented quartzites of the Kinnikinic Quartzite and Quartzite of Grizzly Hill at a high angle, indicating a thick-skinned style. However, the Radio Tower thrust is partly detached in the Devonian Jefferson Formation, just above the mylonite of the Thompson Gulch thrust, in a thin-skinned style. The Baby Joe Gulch thrust cuts across the Radio Tower and Italian Gulch thrusts, signifying it is the youngest in the area. The Baby Joe Gulch thrust cuts indiscriminately across mylonitic rocks and the Beaverhead pluton, characteristic of a thick-skinned style. It is one short segment of a broader anastomosing system between the Poison Creek and Hawley Creek thrusts (Lund, 2018). Provenance studies and low-temperature thermochronology suggest that the Baby Joe Gulch thrust system was active by ca. 67 Ma (Garber and others, 2020; Kaempfer, 2021). Stratigraphic disparities across the Baby Joe Gulch, Italian Gulch, and Radio Tower thrusts suggest reactivation of older normal faults related to the Lemhi arch (Parker and Pearson, 2021). The trace of this thick-skinned fault system also mimics the modern Beaverhead normal fault. Stranded chips of the hanging wall of the basement-involved Baby Joe Gulch thrust occur in the footwall of the Beaverhead normal fault along its trace, suggesting normal reactivation of Cretaceous thick-skinned thrusts during Basin and Range extension.

Horizontal shortening in the Leadore area generally evolved from a more thin- to a more thick-skinned structural style, as deeper detachment horizons were activated during progressive mountain building (Parker and Pearson,

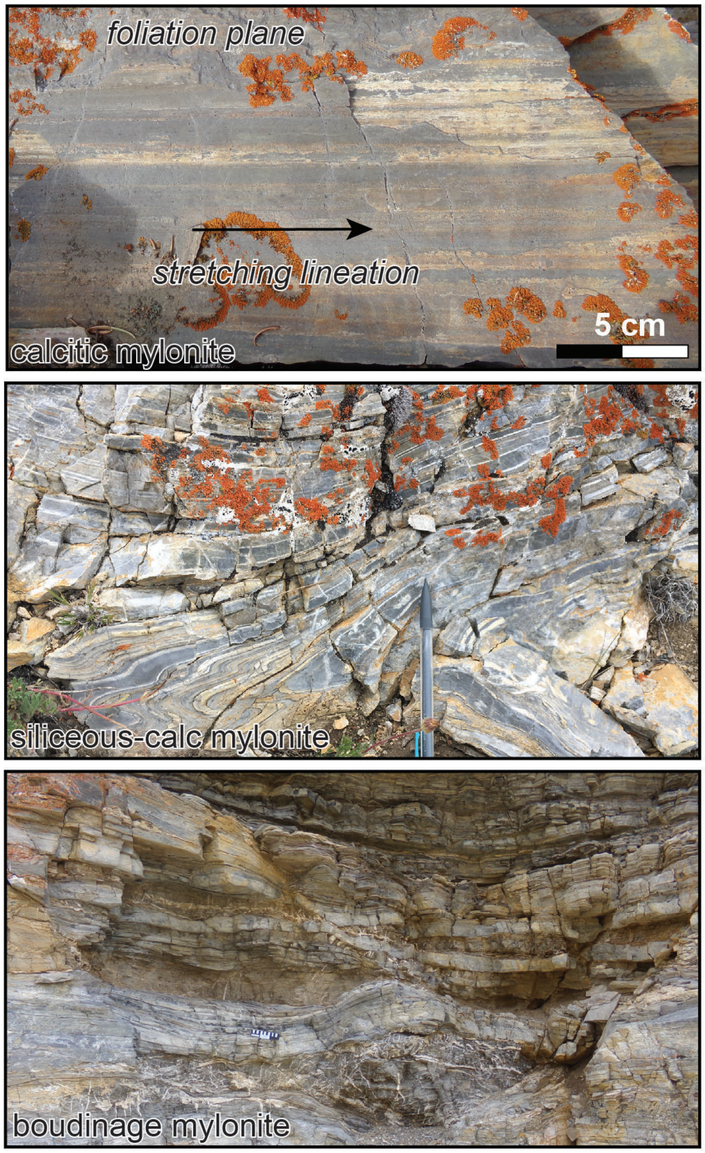

Figure 4. Calcitic, partly siliceous, and boudinaged mylonite tectonofacies of the Thompson Gulch and Railroad Canyon thrusts. Siliceous layers are likely deformed chert. Note upper photo shows planar view, whereas bottom photos show cross-section view. Scale bar in lower photo is 15 cm long, with 1 cm increments.

2021). Thin-skinned deformation of the cover rocks above the Lemhi arch was followed by thick-skinned thrusting of the basement, terminating with reactivation of a preexisting normal fault. Similar patterns of overlapping thin- to thick-skinned thrusts occur throughout the Idaho–Montana fold-thrust belt (e.g., Schmidt and Perry, 1988), but with variable ages that predate flat-slab subduction in the Sierra Nevada (e.g., Orme, 2020). Synthesizing structural interpretations of the Leadore quadrangle with work in the foreland led Parker and Pearson (2021) to propose a double-decker geometry for the Idaho–Montana fold-thrust belt. In this view, the Idaho–Montana fold-thrust belt consists of an upper level of older thin-skinned thrusts that overlap with a lower level of younger thick-skinned thrusts, formed simply by advancing a wedge-shaped deformation zone through a thinly covered basement high.

MINING HISTORY AND ECONOMIC GEOLOGY

This field trip traverses the Leadville (aka Junction) mining district, a small historic lead–silver district along the range front of the Beaverhead Mountains just north of Leadore, Idaho (See Mitchell, 2004 for summary; see Cox and Antonioli, 2017 for field guide). The namesake Leadville (aka Sunset) mine was staked in 1904 and developed the following year (Umpleby, 1913). By 1920, around $100,000 ($1.7 million today) of lead and silver was produced in the district, mostly between 1908 and 1911 during initial production of the Leadville mine (Bell, 1920). While the district was relatively small and short-lived, it hosted numerous shafts, a tunnel, a 25-ton concentrating mill on site, and year-round residents.

Ore consists of argentiferous galena [(Pb, Ag), S] with uncommon pyrite, which replaced brecciated carbonates just above and below fault contacts with the Beaverhead pluton (Umpleby, 1913). The main mineralized zone in the Leadville lode is planar, with a dip of 35–40° toward the south–southwest, likely following permeable zones along the Baby Joe Gulch thrust contact or the adjacent carbonate breccia. Adjacent mylonite contains pyrite with strain fringes, which are concentrated in offset veins (fig. 8 of Parker and Pearson, 2021). This demonstrates that pyrite crystals were rigid during ductile deformation, suggesting that some mineralization could be pre- or syn-kinematic. Mineralization clearly predates the Beaverhead fault, which cuts the deposit in a normal sense. Based on detailed descriptions of Umpleby (1913), the "Calcareous Breccia" unit of Parker and Pearson (2020) is likely the main host rock. Elsewhere, this permeable tectonic breccia has been replaced by dark silica (jasperoid), which has understandably been mistaken for chert (e.g., Ruppel, 1968). While it is clear that mineralization was greatly influenced by the faulting history and tectonostratigraphy within the Leadville mining district, the extraordinary complexity of the geology has proven difficult to predict in the subsurface.

AVAILABLE MAPPING

The 1:62,500-scale Leadore quadrangle was mapped by Ruppel (1968), who identified in the southern portion of his map—and beyond the southern extent of the 1:24,000-scale Leadore quadrangle—a succession of Mesoproterozoic quartzites and siltites that are overlain unconformably by Ordovician through Devonian strata. In the northern portion of his map, which includes the 1:24,000-scale Leadore quadrangle, Ruppel (1968) mapped granite of an uncertain age, complicated thrusts, and "chert" breccias. Mapping at 1:100,000 scale, Ruppel (1998) and Evans and Green (2003) improved upon this work by identifying the Cambrian/Ordovician Beaverhead pluton and simplifying thrust geometries. Using legacy 1:50,000-scale mapping, Lund (2018) identified and named the Baby Joe Gulch and Thompson Gulch thrust systems and reinterpreted the

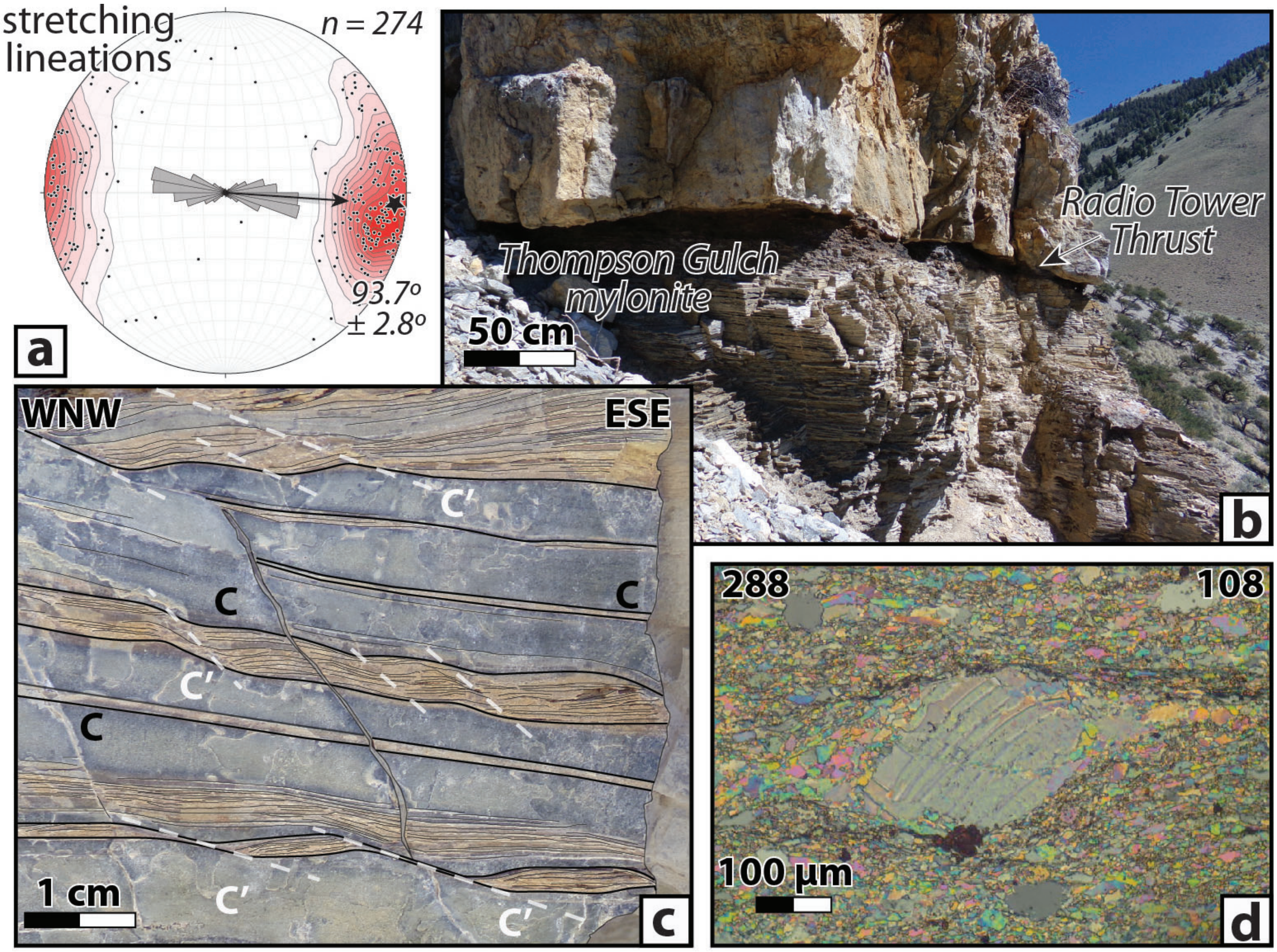

Figure 5. Deformation features of the Thompson Gulch thrust mylonite (Stop 3). (a) Lower hemisphere stereographic projection showing all measured stretching lineations within the Leadore quadrangle. Labeled star shows mean orientation. Inset rose diagram shows mean trend and uncertainty, with data grouped into 10° bins. Kamb contouring at 2σ uncertainty levels. (b) Sharp thrust contact at Stop 2. Note that the black siliceous rock thickens and thins below the Radio Tower Thrust contact. (c) Calcitic mylonite of Thompson Gulch, showing ductile shear planes (C) and antithetic shear bands (C'), which give a top-to-the-right sense of slip. (d) Twinned calcite σ-clast with dynamically recrystallized tails, giving a top-to-the-right sense of slip within the mylonite shown in c. Modified from Parker and Pearson (2021).

lower contact of Paleozoic-on-Mesoproterozoic rocks as an unconformity rather than a fault contact. Further mapping at 1:24,000-scale of the adjacent Bannock Pass quadrangle to the north by Lonn and others (2019) documented that above this newly documented unconformity, middle Paleozoic strata are predominantly east- and southeast-dipping, defining a regional homocline that was inferred to continue southward into the northern Leadore quadrangle. Within this simplified regional geologic context and with the detailed stratigraphic framework of the Jefferson Formation in mind (Grader and others, 2016), Parker and Pearson (2020) mapped the northern part of the Leadore quadrangle at 1:24,000 scale.

Parker and Pearson (2020) recognized that structurally lower rocks within the northern part of the map are structurally overlain by carbonate mylonites along many of the ridges. These mylonites are characterized by a systematic tectonostratigraphy, which reduced the total number of required thrust faults and allowed for individual thrusts to be correlated, defining klippen across much of the map. Parker and Pearson (2020) also identified small-offset, north–northwest-striking normal faults that cut across all other faults, except the modern range-bounding Beaverhead normal fault. Lastly, Parker and Pearson (2020) recognized that two major regional unconformities were likely superimposed upon each other within the map: the sub-Ordovician Lemhi arch unconformity in the south and the intra-Devonian Lemhi arch unconformity to the north. Juxtaposition of strikingly different strata across the Baby Joe Gulch thrust system suggests that older structures were reactivated during Mesozoic and younger faulting in the region and the inherited, pre-thrusting stratigraphic framework likely had a primary influence on the style of thrusting during the Cretaceous (Parker and Pearson, 2021). Given the complexity of the structures within the area, the thinness and heterogeneity of the stratigraphy, and locally poor exposure, future work is likely to continue to refine the mapping, regional stratigraphy, and structural interpretations within the Leadore quadrangle.

ROAD LOG

From the Salmon River in Salmon, Idaho, travel southeast on ID 28 (Main St.), to Leadore, Idaho. It is a 46 mi (74 km), about 45 min, drive. At Leadore, set your odometer to zero, and reset it after each stop. See figure 1 for an overview map of the field trip stops.

0.0 mi (0.0 km) From Leadore, take a left (northeast) on Old ID 28/ID 19 (Dillon St.), following signs toward Smokey Cubs Campground.

0.3 mi (0.5 km) After crossing the Lemhi River, bear left on Old ID 28 (Lemhi Rd.) at the 4-point intersection.

3.2 mi (5.2 km) Continue past the left-hand curve. After passing the last farm field on the right, take a sharp right onto an unnamed dirt BLM road, toward Yearian Cemetery.

4.1 mi (6.7 km) Follow the dirt road up the bench. Bear right, heading toward the "L" and the mouth of Jakes Canyon. Park at the small (Yearian) cemetery, where the road curves to the right, down the bench. This is Stop 1 (fig. 1).

STOP 1
Tectonostratigraphy near the Lemhi arch unconformity

(44.712943°, -113.373260°)

From the parking spot, hike northwest up the alluvial fan toward the small canyon with the dirt road. The contact of interest forms a dip slope on the western side of this small drainage. Follow the small game trail up the ridge, left (west) of the road through the tight canyon, for about 0.5 mi (0.8 km). Where the game trail intersects the highpoint of the road, you'll see a large patch of disturbed ground on the dip slope above, on the hillslope to the right (northeast). Follow the ridge uphill, toward the outcrops above the disturbed patch but on the west side of the ridge, at about 6,530 ft elevation.

Outcrop 1a: Lemhi arch unconformity

(44.718577°, -113.377441°)

Walking along the game trail avoids multiple generations of normal and thrust faults that intersect in Radio Tower Gulch. Structurally beneath these faults, the intact stratigraphy of the Lemhi arch can be observed. Here, a quartzite pebble to cobble conglomerate lies just above the Devonian Lemhi arch unconformity. Clasts are generally well rounded and in matrix support. This compositionally mature conglomerate is only about 1–3 m (3–10 ft) thick, overlying the vitreous upper unit of the Quartzite of Grizzly Hill (Parker and Pearson, 2020). In some places it contains large, meter-scale boulders. The age (Mesoproterozoic?) of the Quartzite of Grizzly Hill and the conglomerate bed above the unconformity is unconstrained (Lonn and others, 2019; Parker and Pearson, 2020).

This unconformity forms a prominent dip slope, with bedding dipping moderately (20–30°) toward the south–southeast. As you walk down the dip slope, upsection, you will encounter laminated dolostones of the Jefferson Formation disconformably overlying this quartzite conglomerate. Near Grizzly Hill, about 5 mi (8 km) north, the unconformity is strongly angular with a northeast-facing direction of about 20°. At this stop, the exceptional thinness of the Jefferson Formation, which is characteristic of the unit at the lowest structural levels, characterizes the apex of the Lemhi arch (Grader and others, 2016). Within the Jefferson Formation, rare tabular beds of matrix-supported dolomite breccias interrupt otherwise intact sedimentary rocks, suggesting layer-parallel slip within very weak beds with high pore-fluid pressures. Rare outcrops of dolomitic sandstones and the Devonian Lemhi arch unconformity are useful pinning points for the numerous north–northwest-striking normal faults that slightly offset the dip panel in an apparent left-lateral sense.

Walk east for about 0.1 mi (0.2 km), down the dip slope and up the other side of the small drainage. Head toward the largest outcrop with patchy trees on the skyline, at about 6,570 ft elevation.

Outcrop 1b: Mylonite above the Lemhi arch unconformity

(44.718059°, -113.374547°)

On the east side of the drainage, the section passes from dolostones of the Jefferson Formation to an overlying carbonate mylonite. These impressive outcrops of carbonate mylonite have a strong foliation and lineation, with late-stage boudins, veins, and normal-sense shear zones (fig. 4). Foliation generally dips to the south–southeast at about 30–40°, parallel with the underlying dip slope. Sub-parallel east–west-stretching lineations are common. Black siliceous intervals form boudins, with pervasive calcite veins indicating late-stage brittle fracturing and filling. In contrast, clean gray calcareous intervals are brilliantly foliated and lineated, with evidence of earlier plastic strain and dynamic recrystallization. Field relationships elsewhere within the northern Leadore quadrangle suggest that mylonitic foliations and lineations formed during a phase of Cretaceous thrusting. Normal-sense brittle-ductile shear zones, boudins, veins, and late-stage faults exposed here may have formed either during vertical flattening and horizontal extension concurrently with the bedding-parallel shear zone, or during early, post-contractional extensional tectonism that exploited the older mylonite. Consider these possible interpretations as we see more of these normal-sense shear zones throughout this trip.

The composition of the mylonite, intact footwall stratigraphy, and contact geometry are consistent with a thin-skinned structural style, with the detachment following the flooding surface of the Lemhi arch, near the thin Sappington and McGowan Creek Formations (fig. 3). Parker and Pearson (2021) hypothesized that this shear zone represents the décollement to the early Idaho–Montana fold-thrust belt. Toward the hinterland, this décollement is likely continuous with a regional thrust flat that forms impressive fold trains in the neighboring Lemhi and Lost River Ranges (e.g., Hait, 1965; Beutner, 1968). As you will see throughout the field trip, this tectonostratigraphy is remarkably consistent throughout the mylonite of the Leadore area, supporting the interpretation of a regional décollement rooted in the thin strata above the Lemhi arch (Parker and Pearson, 2021).

Return to the cars, reset odometer, and drive to stop 2.

0.0 mi (0.0 km) From the cemetery, backtrack to Lemhi Rd. (Old ID 28).

0.9 mi (1.5 km) Take a left (southeast) on Lemhi Rd. (Old ID 28), toward Leadore.

2.9 mi (4.7 km) After the farm fields on the left, near the bench, take a left (east) onto Junction Rd.

3.1 mi (5.1 km) After the center pivot farm field, take an immediate left (north) onto the unnamed dirt BLM road, heading toward the range front. Follow the fence line north.

4.1 mi (6.6 km) At the unmarked intersection, park on the left, before the gate and just outside the northeastern corner of the private section of land. This is Stop 2 (fig. 1).

STOP 2
Tectonostratigraphy near the Baby Joe Gulch thrust

(44.709425°, -113.353993°)

Follow the dirt road uphill, weaving through the small draw and contouring into the side of Jakes Canyon. Once the road begins to contour into Jakes Canyon, head uphill (east) to gain the ridge. Follow the ridge uphill (north), until you reach an old prospecting road that contours across the ridge at about 7,170 ft elevation. Outcrop 2a is on the ridge just below this road, a 1.2 mi (2.0 km) hike from the parking spot.

Outcrop 2a: Footwall tectonostratigraphy

(44.721890°, -113.357528°)

These dolostone outcrops of the Jefferson Formation, in the footwall of the Baby Joe Gulch thrust, are continuous with the stratigraphic section of the previous stop. Primary sedimentary structures, such as fine algal laminations, mud chips, and rare solution breccias, suggest an upright position and a shallow water, restricted depositional environment. These units most likely belong to the Famennian upper Jefferson Formation (D5 and D6 of Grader and others, 2016), which contains abundant anhydrite in a nearby drill hole (e.g., M'Gonigle, 1982). On the hill above, several brecciated outcrops within the Jefferson Formation dot the hillside, structurally just below the shear zone of the Railroad Canyon thrust.

As you walk down the ridge, you'll generally go upsection through the folded tectonostratigraphy of the footwall of the Baby Joe Gulch thrust. Rare outcrops of mottled thick-bedded nodular crinoidal (lime) wackestone with cephalopods (fig. 3) occur just above dolostone of the Jefferson, signifying a change to open marine conditions (Grader and others, 2016). This discontinuous unit is correlative with the False Birdbear member of the Three Forks Formation (Trident Limestone in Montana; Grader and others, 2016). Better exposures on the next hill east show 7 m (23 ft) of black-lavender mudstone and black chert in centimeter-scale layers above, likely correlative to the Sappington Formation (fig. 3; Grader and others, 2016). The disconformity beneath the Sappington Formation is a regional sequence boundary, marking the flooding of the Lemhi arch following Famennian uplift and faulting (Beaverhead uplift of Grader and others, 2016). Above this unit, 5 m (16 ft) of gray-yellow-weathering silty limestone and dolostone, with wavy cleavage and fossil fragments, are tentatively correlative with the McGowan Creek Formation. Above these units you encounter the carbonate mylonite of the Railroad Canyon thrust. While thin, these units are important markers, and this tectonostratigraphy seems to be consistent throughout much of the Leadville mining district.

Structurally above the mylonite, carbonate breccia forms an outcrop belt of cohesive cataclasite. The south-dipping tabular body has subrounded dolomite clasts supported in a calcitic matrix. Unlike the mylonite, which is very fine grained and dynamically recrystallized, a field acid test shows that the breccia is very permeable. This brecciated unit hosts lead–silver ore throughout the Leadville mining district (Umpleby, 1913). Similar breccias have been described in the Gilmore mining district (M'Gonigle, 1982). Rare chert and mylonite clasts are present within the breccia, but overall it is remarkably monolithologic and in many places occurs between undeformed beds, perhaps reflecting deformation and replacement of evaporite beds (M'Gonigle, 1982).

Continue walking down the ridge. After the last brecciated outcrops, keep an eye on the float. Find the contact between the red-weathering slopes of the Beaverhead pluton and the gray to yellow limestone breccia, at about 6,830 ft elevation. Follow this contact down (west) into Jakes Canyon, where it intersects the contouring road at about 6,710 ft elevation.

Outcrop 2b: Baby Joe Gulch Thrust

(44.719372°, -113.359532°)

This prominent color change marks the Baby Joe Gulch thrust, making it easy to trace through the landscape. The view to the west, across Jakes Canyon, shows the cross-sectional geometry of the fault (fig. 6). The fault plane dips to the south–southwest (198°) at 38°. In the footwall, the fault cuts across a section of mylonite that lies below the breccia that marks the fault contact here. The complete section of mylonite, the Devonian Jefferson Formation, and Mesoproterozoic (?) Quartzite of Grizzly Hill have been folded in an open anticline. Note that the quartzite outcrop is truncated by the steep Radio Tower Gulch thrust, with apparent thrust (or left-lateral) offset.

In contrast to the Devonian unconformity we have seen in the footwall of the Baby Joe Gulch thrust, nearby the hanging wall stratigraphy consists of Beaverhead pluton intruded into Mesoproterozoic quartzite, nonconformably underlying Ordovician Kinnikinic Quartzite (Lund and others, 2010). These two sections represent the apex and flank of the Lemhi arch, respectively, bracketing the hinge line (fig. 3). These stratigraphic relationships suggest normal fault offset before the latest Devonian, with thrust reactivation during the Cretaceous (Parker and Pearson, 2021).

Continue walking down the road (south), contouring around the left (east) and into the small drainage. At about 6,650 ft elevation, you'll see a mylonite outcrop uphill (northeast) of the road.

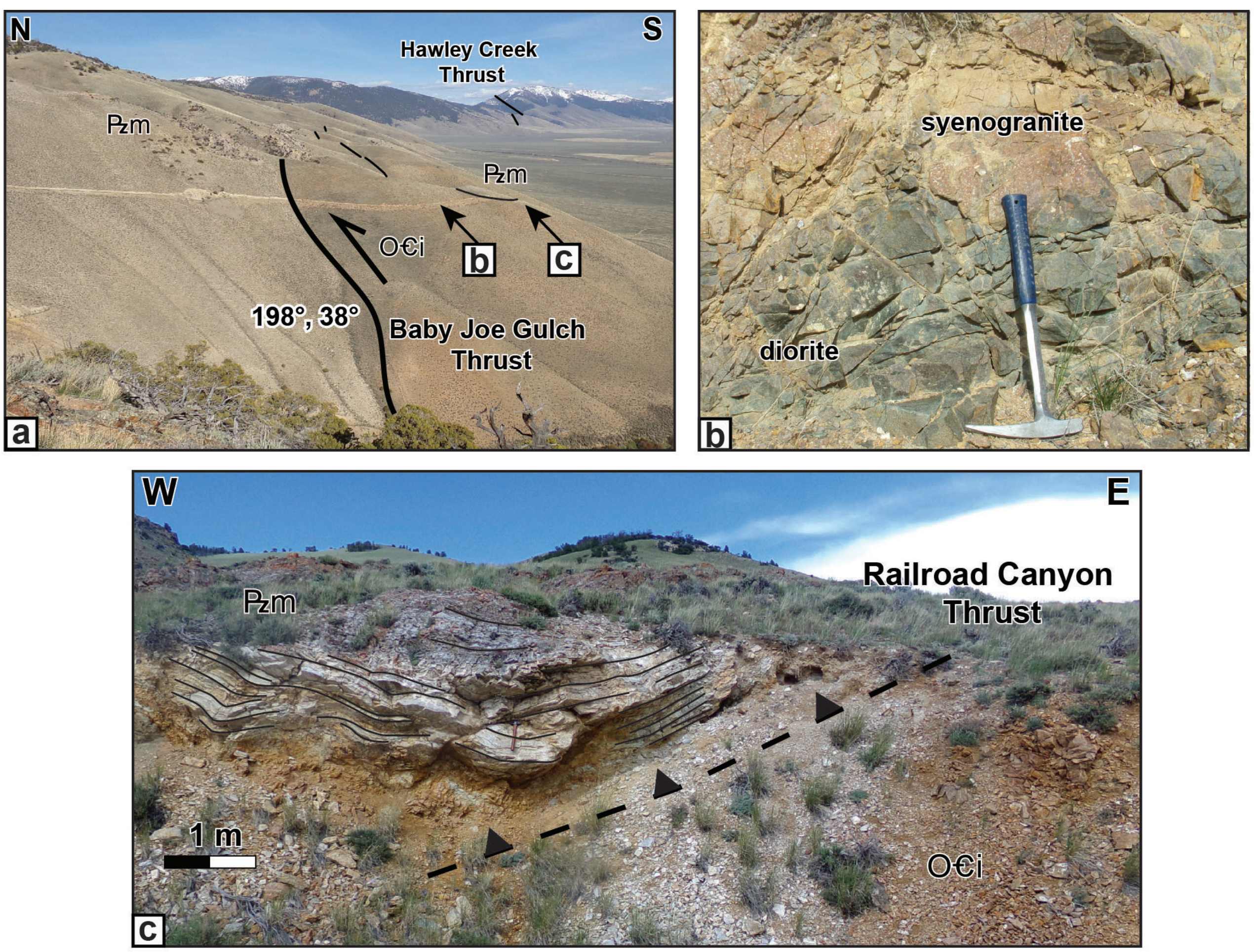

Figure 6. Annotated photo of faults in Jakes Canyon, looking west from Stop 2. Modified from Parker and Pearson (2021). See figure 2 for abbreviated unit names. Modified from Parker and Pearson (2021).

Outcrop 2c: Beaverhead pluton and hanging wall mylonite

(44.717235°, -113.358676°)

Along the road, between outcrops 2b and 2c, there are rare outcrops of the Beaverhead pluton, where clasts of pink potassium–feldspar-rich syenogranite are included in dark-green, altered diorite (fig. 6). Often the pluton is concealed by reddish, sparsely vegetated slopes like seen along this road. Where it crops out near Hawley Creek (fig. 7), the Beaverhead pluton yielded a mean U-Pb zircon age of 488 ± 5 Ma (Lund and others, 2010).

At the next road cut, a klippe of mylonite overlies the poorly exposed Cambrian/Ordovician Beaverhead pluton (fig. 6). This cryptic outcrop is typical of the Railroad Canyon thrust, the structurally highest mylonite in the field trip area. This younger-on-older relationship is interpreted as a bedding-parallel thrust fault, like the one observed at stop 1. It is unclear whether the omitted tectonostratigraphy (e.g., Jefferson Formation, breccia, Kinnikinic, etc.) is the consequence of a nonconformity, attenuation in the shear zone, or local downcutting in the direction of transport during thrusting.

In detail, the mylonitic foliation parallels abundant similar folds, many of which are sheath folds. The foliation, and in places a weak lineation, has been folded by open outcrop-scale folds and in places is truncated by late-stage brittle faults. See if you can find any dolomite clasts within the calcitic mylonite. Follow the slightly irregular fault contact, between the mylonite and the Beaverhead pluton, around this small outcrop to get a sense of the low-angle fault geometry.

In summary, the tectonostratigraphy suggests that the Railroad Canyon thrust is detached in weak silty limestones, mudstones, and possibly evaporites, just above the uppermost Jefferson Formation. The consistency of this tectonostratigraphy suggests that the shear zone, defined by mylonite and breccia, follows a major unconformity in a thin-skinned fashion. The Baby Joe Gulch thrust postdates the Railroad Canyon thrust, dips moderately to the south, cuts across all lithologic markers, and exposes plutonic rocks in its hanging wall, giving it a thick-skinned structural style. The Baby Joe Gulch thrust apparently reactivated an older Paleozoic normal fault of the Lemhi arch.

Hike 0.8 mi (1.3 km) back down to the parking spot, reset odometer.

0.0 mi (0 km) From the parking area for stop 1, drive east along unmarked roads. Aim for the mouth of the next major canyon to the east, Thompson Gulch.

1.0 mi (1.66 km) Park at the intersection at the mouth of the canyon.

STOP 3
Radio Tower thrust and Thompson Gulch mylonite

(44.711244°, -113.334105°)

Hike about 0.5 mi (0.8 km) into Thompson Gulch. Just after the bedrock constriction, contour up the slope on the left, toward the pinnacles at about 6,780 ft.

Outcrop 3a: Radio Tower thrust contact

(44.717119°, -113.334947°)

The pinnacle exposes the sharp contact of the Radio Tower thrust, marked by a yellow-tan dolostone breccia on top of the Thompson Gulch thrust mylonite (fig. 5).

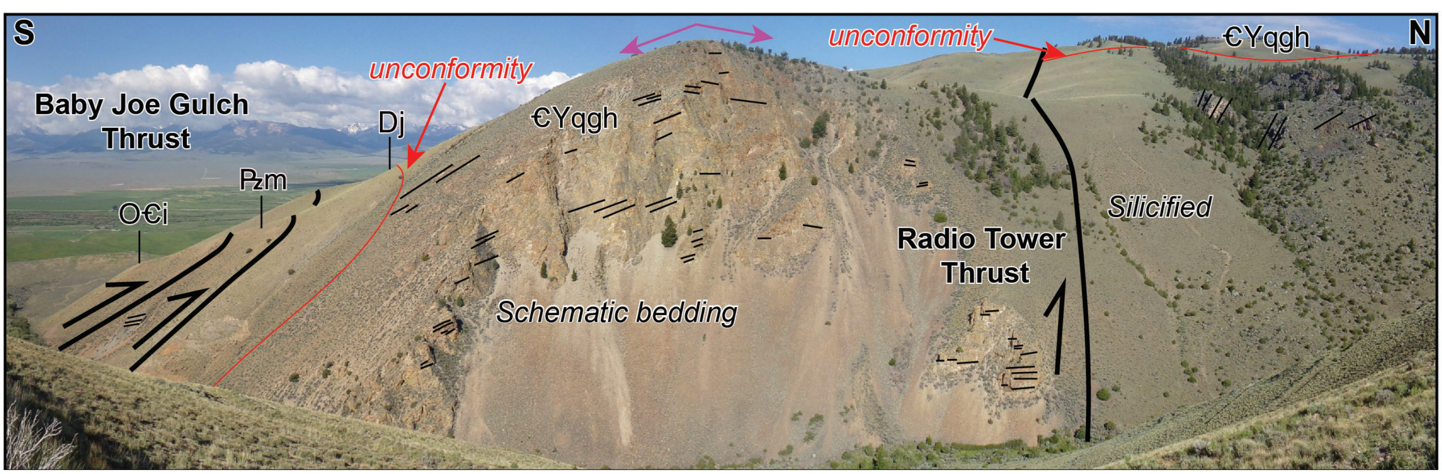

Figure 7. Annotated photos showing rocks of Stop 1. (a) Cross-section of Baby Joe Gulch thrust, as viewed from the west side of Jakes Canyon. Note correlative Hawley Creek thrust to the east. (b) Intrusive contact between syenogranite and diorite of the Beaverhead pluton. (c) Railroad Canyon Thrust contact, which puts younger carbonate mylonite on the older Beaverhead pluton. See figure 2 for abbreviated unit names. Modified from Parker and Pearson (2021).

In places, the contact cuts downsection slightly, leaving behind large blocks of black siliceous rocks. Variably thick fault gouge marks the base of the fault contact. A polished, lineated clay layer a few centimeters thick underlies the fault gouge in some spots, possibly representing a late-stage brittle fault in siliceous rocks. Mylonitic chips within this damage zone are often imbricated or inclined. The base of the outcrop is a clean carbonate mylonite, with stretching lineations and C–C' fabrics that suggest a top-to-the-east-southeast thrust sense of motion (fig. 5). In thin sections, σ-clasts and strain fringes give the same sense of slip.

The hanging wall consists of about a meter of tabular breccia, similar to those observed at previous stops. Above, dolostone of the Jefferson Formation is fractured, but upright sedimentary structures are still visible, including flat laminations, mud chips, ooids, scours, mud cracks, and possible stromatolites. On the ridge above, rare outcrops of the thick-bedded, mottled limestone and overlying fine-grained sandstone signify the transition from restricted to open shelf and shoreface conditions during flooding of the Lemhi arch (False Birdbear member and Sappington Formation). In the footwall, the clean gray and tan banded calcite mylonite is likely deformed McGowan Creek Formation. Dark, more siliceous intervals may be deformed Sappington Formation.

Though the stratigraphic offset clearly has a thrust-sense, normal-sense shear zones are common throughout the outcrop. As discussed earlier, this may be representative of either late-stage extension or syn-contractional flattening within the shear zone, which is common in weak ductile rocks, particularly when they are bounded by much stronger units. The temperature conditions during faulting were such that dolomite and siliceous rocks were brittle, whereas calcitic rocks deformed plastically. This observation agrees well with maximum temperature constraints from the field trip area, which range from 244 to 281°C (±25) in the Pennsylvanian to Devonian section (Parker and others, 2022). The minor thrust offset (<50 m) of the Radio Tower thrust suggests that it may be a late-stage brittle imbricate to the Thompson Gulch thrust, perhaps accommodating strain variations between stronger dolostones and weaker limestones. To the west, the Radio Tower thrust can be traced into the high-angle thick-skinned fault contact observed in Jakes Canyon (fig. 2), suggesting the fault-geometry transitions from a more thin- to a more thick-skinned segment as it encountered much stronger quartzites of the Lemhi arch.

Contour north, across the hill slope to the spur ridge, and follow it down toward Thompson Gulch.

Outcrop 3b: Thompson Gulch mylonite

(44.718369°, -113.334110°)

Along this spur ridge you'll walk downsection through the Radio Tower thrust fault zone, into mylonite of the Thompson Gulch thrust. This extensive mylonite forms klippen throughout the field trip area, defining the shear zone of the Thompson Gulch thrust. It varies from clean calcite mylonite to brilliantly banded siliceous–calcitic mylonite, likely reflecting chert-rich intervals that are common in the Mississippian Middle Canyon and Scott Peak Formations. The mylonite of the Thompson Gulch thrust is about 37 m (120 ft) thick here. Eventually you'll get into Pennsylvanian Snaky Canyon Formation in the footwall.

Hike out of Thompson Gulch, back to the parking spot, reset odometer.

0.0 mi (0 km) From the parking area for Stop 2, reverse course back to the 4-way intersection of Old ID 28 (Lemhi Rd.) and ID 29.

3.0 mi (4.8 km) Take a left (northeast) on ID 29, toward Smokey Cubs Campground (fig. 1).

6.4 mi (10.3 km) Take a left into Smokey Cubs Campground. Bear right, away from the bathrooms, to cross the creek.

6.7 mi (10.8 km) Park on the right, near the water pump.

STOP 4
Railroad Canyon mylonite

(44.703965°, -113.293063°)

Hike northeast along the flat dirt road, into Railroad Canyon (aka Canyon Creek), for as long as you'd like. Head back when you've seen enough mylonite.

Outcrop 4a: Railroad Canyon mylonite and Lemhi arch flank stratigraphy

(44.709658°, -113.285414°)

The canyon mouth marks the Beaverhead (normal) fault, with outcrop bands of Ordovician Kinnikinic Quartzite and Beaverhead pluton marking remnants of truncated thrust faults. The prospect pits along the range front continue to the Leadville Mine, less than a mile (1.6 km) to the west. In contrast to previous stops, here quartzite of the Ordovician Kinnikinic and fossiliferous dolostone of the Ordovician/Silurian Saturday Mountain Formation occur above the Beaverhead pluton. In the float, look for Halysites (chain coral), a tabulate coral that is diagnostic of the Ordovician and

Silurian (fig. 3). The overlying Jefferson Formation is at least 150 m thick (490 ft) and contains reefs and impressive thick-bedded cycles containing amphipora (spaghetti rock fossils), which last occurred in Frasnian (Late Devonian) time (fig. 3; Grader and others, 2016).

This older, thicker, more complete stratigraphic section represents the western flank of the Lemhi arch, which is typical of east-central Idaho. In this more basinward section, the younger (Devonian) Lemhi arch unconformity is less pronounced (fig. 3). The stratigraphic discontinuity across the Baby Joe Gulch thrust and its imbricates suggests pre-Devonian (Famennian) normal offset, which downdropped the flank of the Lemhi arch (Beaverhead uplift of Grader and others, 2016). Thrust reactivation of the Baby Joe Gulch fault (and possibly its imbricates) in the Cretaceous shortened this important hinge line, while later Basin and Range normal faulting seems to have reactivated it again in the Cenozoic.

The constriction of the canyon marks the Railroad Canyon thrust contact, where steep mylonite outcrops (fig. 8a) have an apparent thickness of up to 80 m (260 ft). In detail, foliation parallels axial surfaces of flattened sheath folds and rootless folds (fig. 8b), suggesting local shear zone flattening. Rare boudins of dark, more siliceous rock, within attenuated mylonite layers (fig. 8c), suggests similar rheologic contrasts as discussed at previous stops. Gently plunging east–west-stretching lineations are indistinguishable with those of the Thompson Gulch thrust.

The Railroad Canyon thrust contact dips about 30° to the southeast (fig. 8a), wrapping around the canyon. It can be traced to the west, structurally above the Beaverhead pluton, in the hanging wall of the Baby Joe Gulch thrust (fig. 2). Removing slip on the Baby Joe Gulch thrust and its imbricates establishes continuity between the Thompson Gulch and Railroad Canyon thrusts. This suggests that they were once part of the

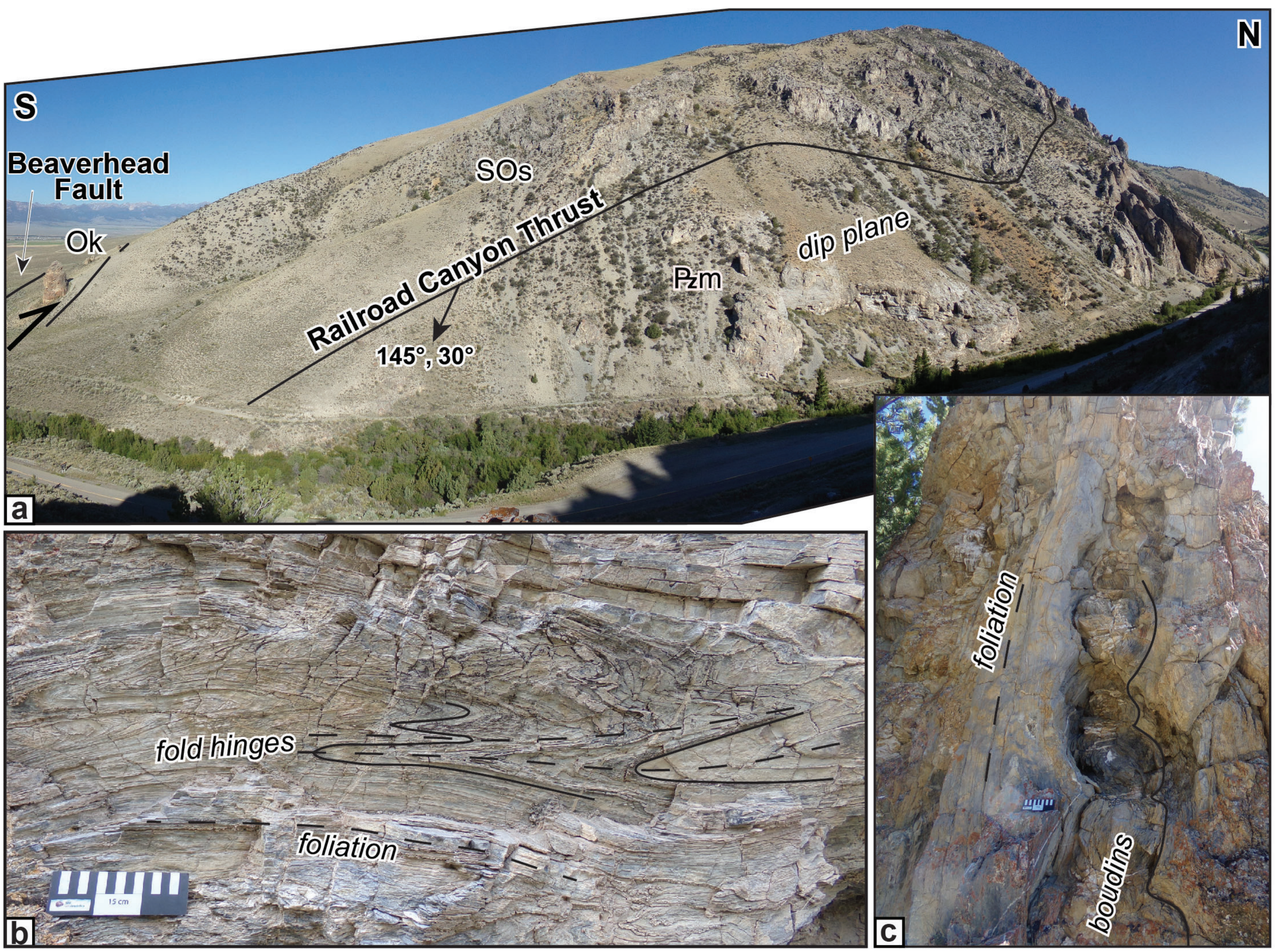

Figure 8. Annotated photos of Railroad Canyon thrust (Stop 4). (a) Fault relationships as viewed from the eastern side of Railroad Canyon, with label on the hanging wall. Mean dip of the thrust plane shown by labeled arrow. See figure 2 for abbreviated unit names. (b) Flattened similar folds within the mylonite showing high ductile strain. Resistant siliceous bands highlight folds. (c) Rheological contrasts between brittle, more siliceous boudins, and ductile, more calcitic mylonites.

same thin-skinned thrust, with a detachment following nonconformities and disconformities up and over the low-relief Lemhi arch.

The complicated relationships observed during this field trip within the northern Leadore quadrangle can be summarized by a simple series of deformation events. The stratigraphy suggests pre-Devonian normal faulting, with the resultant Lemhi arch basement high persisting until it was flooded in the latest Devonian (Famennian; Grader and others, 2016). During the Cretaceous, top-to-the-east motion along the Thompson Gulch–Railroad Canyon thrust system occurred in a thin-skinned fashion at depths of around 6–9 km (4–6 mi; Parker and others, 2022). A lateral ramp, following weak rocks near the base of the carbonate package, likely connected the detachment across the variable hinge line strata that drape the Lemhi arch. Late thick-skinned slip along the Baby Joe Gulch thrust and its imbricates cut this mylonite, during more north–south-oriented shortening above a deeper detachment within basement rocks of the Lemhi arch. Normal slip along the Beaverhead fault may have taken a shortcut and rooted into the thick-skinned Baby Joe Gulch thrust at depth, leaving behind a "perched basement wedge" (Sales, 1983; Lageson, 1989). In addition to being persistent weaknesses, the stratigraphically controlled thin-skinned thrusts of the Thompson Gulch–Railroad Canyon thrust system and the reactivated thick-skinned thrusts of the Baby Joe Gulch thrust system seem to be important conduits and seals that focused mineralization in the small but complex Leadville mining district.

REFERENCES

Bell, R.N., 1920, Twenty-first annual report of the mining industry of Idaho for the year 1919: Report of inspector of mines, 180 p.

Beutner, E.C., 1968, Structure and tectonics of the southern Lemhi Range, Idaho: State College, Penn., Pennsylvania State University, Ph.D. thesis, 106 p., 3 plates.

Cox, B., and Antinioli, T., 2017, Ore controls of the Leadville (Junction) and Gilmore mining districts, Lemhi County, Idaho: A field trip guide: Northwest Geology, v. 46, p. 93–100.

Evans, K.V., and Green, G.N., 2003, Geologic map of the Salmon National Forest and vicinity, east-central Idaho: U.S. Geological Survey Geologic Investigations Series, I-2765, 2 sheets, scale 1:100,000.

Garber, K.L., Finzel, E.S., and Pearson, D.M., 2020, Provenance of synorogenic foreland basin strata in southwestern Montana requires revision of existing models of Laramide tectonism: North American Cordillera: Tectonics, v. 39, 26 p.

Grader, G.W., Isaacson, P.E., Doughty, P.T., Pope, M.C., and Desantis, M.K., 2016, Idaho Lost River shelf to Montana craton: North American Late Devonian stratigraphy, surfaces, and intrashelf basin, *in* Playton, T.E., Kerans, C., and Weissenberger, J.A.W., eds., New advances in Devonian carbonates: Outcrop analogs, reservoirs, and chronostratigraphy: Society of Sedimentary Geology Special Publication 107, p. 347–379.

Hait, M.H., 1965, Structure of the Gilmore area, Lemhi Range, Idaho: State College, Penn., Pennsylvania State University, Ph.D. thesis, 134 p., 3 plates.

Kaempfer, J.M., 2021, Deep-time tectono-thermal history of the northern US Cordillera: Understanding zircon (U-Th)/He thermochronology and its application to Idaho–Montana basement rocks: Ph.D. thesis, University of Illinois, 141 p.

Lageson, D.R., 1989, Reactivation of a Proterozoic continental margin, Bridger Range, southwestern Montana, *in* French, D.E., and Grabb, R.F., 1989 Field conference guidebook: Geologic resources of Montana: Montana Geological Society, p. 279–298.

Link, P.K., Todt, M.K., Pearson, D.M., and Thomas R.C., 2017, 500–490 Ma detrital zircons in upper Cambrian Worm Creek and correlative sandstones, Idaho, Montana, and Wyoming: Magmatism and tectonism within the passive margin: Lithosphere, v. 9, no. 6., p. 910–926.

Lonn, J.D., Elliott, C.G., Stewart, D.E., Mosolf, J.G., Burmester, R.F., Lewis, R.S., and Pearson, D.M., 2019, Geologic map of the Bannock Pass 7.5' quadrangle, Beaverhead County, Montana, and Lemhi County, Idaho: Montana Bureau of Mines and Geology Geologic Map 76, 1 sheet, scale 1:24,000.

Lucchitta, B.K., 1966, Structure of the Hawley Creek area, Idaho-Montana: State College, Penn., Pennsylvania State University, Ph.D. thesis, 203 p., 2 plates.

Lund, K., 2018, Geologic map of the central Beaverhead Mountains, Lemhi County, Idaho, and Beaverhead County, Montana: U.S. Geological Survey Scientific Investigations Map 3413, 1 sheet, scale 1:50,000.

Lund, K., Aleinikoff, J.N., Evans, K.V., duBray, E.A., Dewitt, E.H., and Unruh, D.M., 2010, SHRIMP U-Pb dating of recurrent Cryogenian and Late Cambrian–Early Ordovician alkalic magmatism in central Idaho: Implications for Rodinian rift tectonics: Geological Society of America Bulletin, v. 122, p. 430–453.

M'Gonigle, J.W., 1982, Devonian carbonate-breccia units in southwestern Montana and Idaho; A review of brecciating mechanisms, *in* Powers, R.B., ed., Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, v. 2, p. 677–690.

Mitchell, V.E, 2004, History of the Leadville, Kimmel, and Baby Joe Mines, Lemhi County, Idaho: Idaho Geological Survey Staff Report 04-1, 35 p.

Orme, D.A., 2020, New timing constraints for the onset of Laramide deformation in southwest Montana challenge our understanding of the development of a thick-skinned structural style during flat-slab subduction: Tectonics, v. 39, no. 12., 8 p.

Parker, S.D, and Pearson, D.M., 2020, Geologic map of the northern part of the Leadore quadrangle, Lemhi County, Idaho: Idaho Geological Survey Technical Report T-20-03, 1 sheet, scale 1:24,000.

Parker, S.D, and Pearson, D.M., 2021, Pre-thrusting stratigraphic control on the transition from a thin-skinned to thick-skinned structural style: An example from the double-decker Idaho–Montana fold-thrust belt: Tectonics, v. 40, no. 5., 31 p.

Parker, S.D, Pearson, D.M., and Finzel, E.S., 2022, A thermal profile across the Idaho–Montana fold-thrust belt reveals a low-relief orogenic wedge that developed atop a pre-orogenic basement high: Lithosphere, v. 2022, 28 p.

Ruppel, E.T., 1968, Geologic map of the Leadore quadrangle, Lemhi County, Idaho: U.S. Geological Survey Geologic Quadrangle map GQ-733, 1 sheet, scale 1:62,500.

Ruppel, E.T., 1986, The Lemhi arch: A Late Proterozoic and early Paleozoic landmass in central Idaho: AAPG Memoir, v. 41, p. 119–130.

Ruppel, E.T., 1998, Geologic map of the eastern part of the Leadore 30' x 60' quadrangle, Montana and Idaho: Montana Bureau of Mines and Geology Open-File Report 372, 1 plate, scale 1:100,000.

Sales, J.K., 1983, Collapse of Rocky Mountain basement uplifts, *in* Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists, p. 79–97.

Schmidt, C.J., and Perry, W.J., 1988, Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir, v. 171, 582 p.

Scholten, R., 1957, Paleozoic evolution of the geosynclinal margin north of the Snake River Plain, Idaho–Montana: Geological Society of America Bulletin, v. 68, p. 151–170.

Scholten, R., and Ramspott, L.D., 1968, Tectonic mechanisms indicated by structural framework of central Beaverhead Range, Idaho–Montana: Geological Society America Special Paper, v. 104, 59 p.

Skipp, B, 1988, Cordilleran thrust belt and faulted foreland in the Beaverhead Mountains, Idaho and Montana, *in* Schmidt, C.J., and Perry, W.J., eds., Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir, v. 171, 2 plates, p. 237–266.

Sloss, L.L., 1954, Lemhi arch, a mid-Paleozoic positive element in south-central Idaho: Bulletin of the Geological Society of America, v. 65, p. 365–368.

Umpleby, J.B., 1913, Geology and ore deposits of Lemhi County, Idaho: U.S. Geological Survey Bulletin, v. 528, 182 p.

Yonkee, W.A., and Weil, A.B., 2015, Tectonic evolution of the Sevier and Laramide belts within the North American Cordillera orogenic system: Earth-Science Reviews, v. 150, p. 531–593.