POST-BELT SUPERGROUP MESOPROTEROZOIC TO CAMBRIAN ROCKS OF THE LEATON GULCH AREA, EAST OF CHALLIS, IDAHO

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ABSTRACT

The time interval between ca. 1800 Ma and 700 Ma is generally thought to have been a time of geologic quiescence in the northern Rocky Mountains of Idaho and Montana, punctuated by Mesoproterozoic deposition of >18 km of fine-grained strata of the Belt–Purcell Supergroup. Though most workers agree that Belt Basin strata record intracratonic crustal extension that did not result in continental breakup and formation of a passive margin succession, some recent workers argue for <1.3 Ga shuffling of Nuna supercontinent fragments near the western margin of the Belt Basin prior to reassembly of Rodinia; thus, a better understanding of geologic events during and after late Belt deposition is important for constraining the Mesoproterozoic to Neoproterozoic geologic evolution of western North America. Prior timing constraints on Belt–Purcell Supergroup strata suggest that deposition initiated before ca. 1470 Ma and was complete by ca. 1370 Ma plutonism that intruded Lemhi subbasin rocks west of Salmon, Idaho. These strata also contain rare ca. 1410–1390 Ma detrital zircons, which represent near-depositional age magmatism. However, the correlation of the stratigraphically highest Mesoproterozoic rocks in western Montana and northeastern Washington—including the Deer Trail Group and Buffalo Hump Formation—to the Belt Supergroup has been demonstrated to be incorrect on the basis of the depositional environment and geochronological data (Box and others, 2020; Brennan and others, 2021).

Here, we provide a progress report of ongoing field and zircon U-Pb geochronologic studies in the Leaton Gulch area of the northern Lost River Range/Pahsimeroi Mountains. These strata were previously mapped by McIntyre and Hobbs (1987) as “Ordovician to Proterozoic” in age. Our preliminary results suggest that this area exposes ca. 1336 Ma, post-Belt Supergroup Mesoproterozoic sedimentary rocks. These rocks thus represent a unique record of post-Belt Supergroup geologic time in the northern Rocky Mountains. These post-1336 Ma strata are overlain unconformably by a relatively thin section of Neoproterozoic to Ordovician strata (Wilbert and Summerhouse Formations). The Wilbert and associated rocks define the western flank of the latest Cambrian and Early Ordovician Lemhi arch.

INTRODUCTION

The geologic record after the ca. 1800 Ma assembly of the North American craton and prior to the post-780 Ma breakup of the supercontinent Rodinia represents nearly 1 billion years of Earth history and encompasses the tenure of the global supercontinent Nuna (also called Columbia), crustal growth during protracted Yavapai–Mazatzal and Picuris tectonism in southwestern Laurentia (e.g., Whitmeyer and Karlstrom, 2007; Daniel and others, 2013; Aronoff and others, 2016), development of the ~1450 Ma Belt Basin (e.g., Winston and Link, 1993), presumed breakup of Nuna after ca. 1300 Ma (e.g., Medig and others, 2014; Kirscher and others, 2020), and reassembly of Rodinia during ca. 1300–1000 Ma Grenville-age orogenesis (e.g., Gower, 1996; Mosher, 1998). However, throughout much of Montana and Wyoming, the geologic record of this interval is largely missing given that early Paleozoic passive margin sedimentary rocks generally sit upon Archean–Proterozoic crystalline rocks in a profound (>1 Ga) unconformity (e.g., Sloss, 1988). An exception to this is in western Montana and Idaho, where >18-km-thick strata of the Mesoproterozoic Belt–Purcell Supergroup are preserved. Many geologists consider these rocks to record failed intracratonic rifting (e.g., Winston and Link, 1993; Lonn and others, 2020). In contrast, others have suggested that shuffling of Nuna supercontinent fragments near the western margin of the Belt Basin occurred during or after the late stages of Belt deposition (after ca. 1400 Ma.), followed by reassembly during formation of the supercontinent Rodinia and final rifting after ca. 780 Ma (e.g., Kirscher and others, 2020).

Though free of body fossils and with few syndepositional, datable igneous rocks, we know that deposition of the Belt–Purcell Supergroup initiated before emplacement of ca. 1470 Ma mafic sills (Anderson and Davis, 1995; Sears and Chamberlain, 1998), and deposition is thought to have completed by ca. 1370 Ma plutonism that intruded Lemhi subbasin rocks west of Salmon, Idaho (Evans and Zartman, 1990; Doughty and Chamberlain, 1996, 2008; Aleinikoff and others, 2012; Bookstrom and others, 2016). In Idaho, Lemhi Group and overlying rocks of the Swauger, Lawson Creek, and Apple Creek Formations are over ~15 km thick and are thought to correlate with Missoula Group strata that define the upper Belt Supergroup in western Montana (Link and others, 2007; Burmester and others, 2016; Lonn and others, 2020). These strata contain rare detrital zircons that suggest ~1410–1390 Ma maximum depositional ages, which may represent near-depositional age magmatism (Aleinikoff and others, 2012; Link and others, 2016).

Where studied in detail, upper Belt Supergroup rocks are overlain unconformably by Neoproterozoic to Cambrian rift and early passive margin rocks (Deiss, 1935) now correlated with the Windermere Supergroup (Stewart, 1972). However, the Garnet Range Formation—considered to be part of upper Belt strata of the Missoula Group in western Montana—records a marked shift toward compositional immaturity (i.e., increase in detrital feldspar, mica, and magnetite), with a concurrent appearance of lensoidal sand bodies and large-scale hummocky cross stratification; these observations suggest an important change in depositional environment and provenance, which may suggest that these rocks are distinct from underlying strata of the Belt–Purcell Supergroup (Kidder, 1992; Winston and Link, 1993). One detrital mica grain from the Garnet Range Formation produced a robust Ar/Ar age of 1336 ± 14 Ma, which hints at a post-Belt Supergroup age of these strata (Ross and Villeneuve, 2003).

In northeastern Washington, strata of the Deer Trail Group were presumed to be equivalent to that of the upper Belt Supergroup (Evans, 1987; Miller and Whipple, 1989). However, the uppermost exposed unit, the Buffalo Hump Formation, which has a lower unconformity but was assigned to underlying strata of the Deer Trail Group, recently produced many U-Pb detrital zircon (DZ) ages of ca. 1100 Ga (Box and others, 2020). Further, a subsidiary DZ age peak at ca. 760 Ma supports a recorrelation of Buffalo Hump Formation rocks to overlying strata of the Chuar-Uinta Mtn-middle Pahrump (ChUMP) succession stratigraphically below the Windermere Supergroup (Brennan and others, 2021). Though the Buffalo Hump Formation unconformably overlies subjacent Deer Trail Group strata (Evans, 1987), the stratigraphically lower Wabash–Detroit Formation, which was also previously correlated with upper Belt strata, produced ca. 1300, post-Belt Supergroup DZs (Box and others, 2020). Taken together, these results suggest that the Deer Trail Group and Buffalo Hump Formation contain a post-Belt Supergroup, pre-ChUMP record of ca. 1300 Ma sedimentation in the northern Rocky Mountains.

One of the thickest successions of presumed Belt Supergroup-equivalent strata in Idaho is exposed in the northern Lemhi Range (fig. 1); the upper part of this succession is thought to define the upper part of the Belt section in Idaho (Burmester and others, 2016). Approximately 15 km to the southwest across a major Basin and Range fault, in the northern Lost River Range/Pahsimeroi Mountains near Leaton Gulch, McIntyre and Hobbs (1987) identified an enigmatic succession of predominantly siliclastic strata exposed over an ~50 km^2 area. Lower rocks in this succession lack trace fossils and the upper exposed part of the section is bioturbated; however, uncertainties with regional correlations led McIntyre and Hobbs (1987) to assign an ambiguous “Ordovician to Proterozoic” age. The proximity of Leaton Gulch strata to upper Belt Supergroup rocks and the appearance of trace fossils in the upper part of the section suggest that these rocks may record the interval of geologic time during and after the late stages of Belt deposition. Here, we provide a progress report of ongoing field-based and zircon U-Pb geochronology-based studies in the Leaton Gulch area of the northern Lost River Range/Pahsimeroi Mountains in an attempt to evaluate the chronostratigraphic position and stratigraphy of these rocks (fig. 1). Our results suggest that this area exposes Mesoproterozoic (ca. 1336 Ma), post-Belt Supergroup sedimentary rocks and a relatively thin section of Neoproterozoic to Ordovician section (Wilbert and Summerhouse Formations) that likely defines the western flank of the latest Cambrian and Early Ordovician Lemhi arch. These rocks thus represent a unique opportunity to investigate the provenance and depositional setting of an enigmatic interval of geologic time in the northern Rocky Mountains.

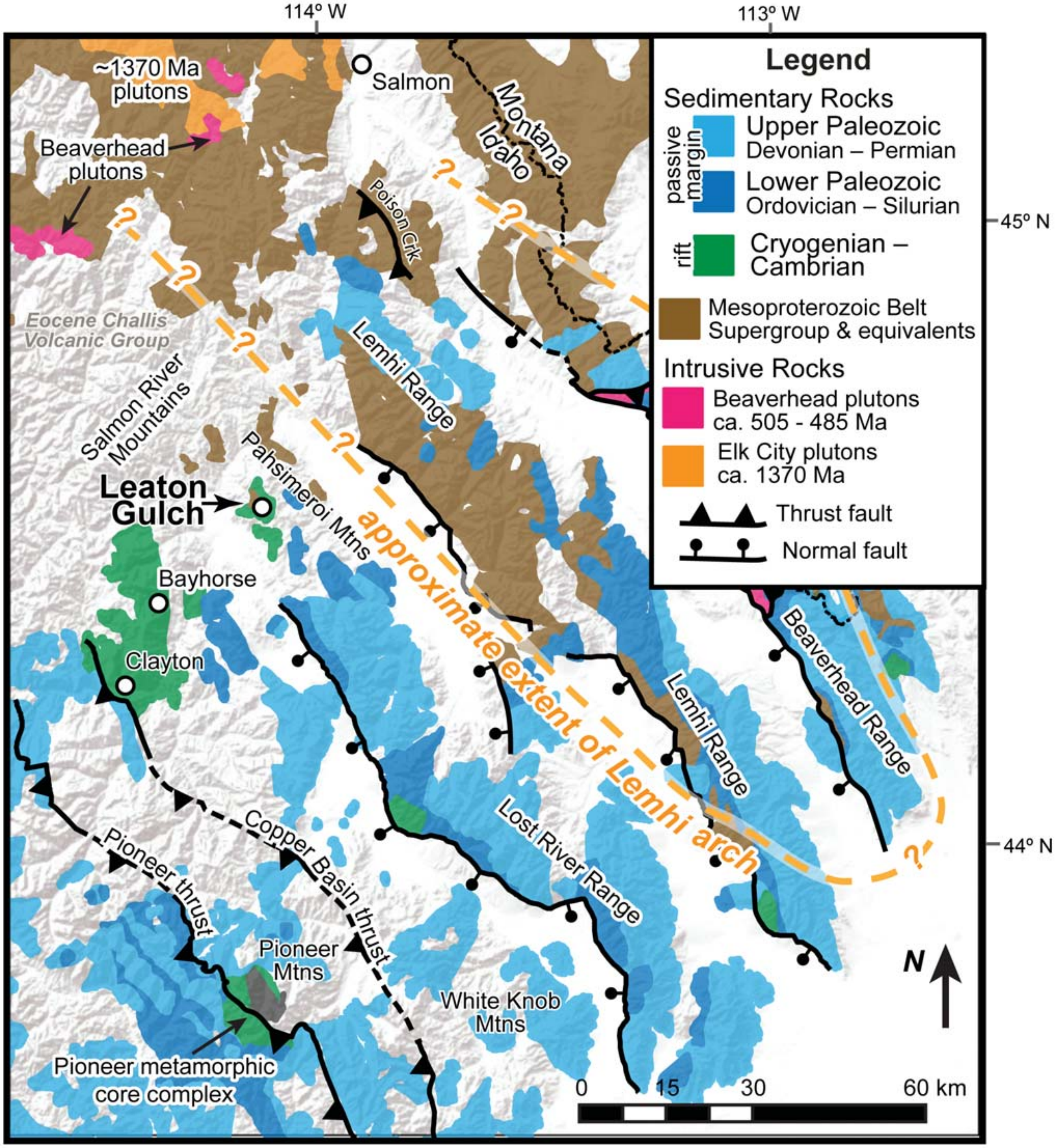

Figure 1. Index map showing Leaton Gulch area in the context of the regional geology of eastern Idaho (modified from Brennan and others, in review).

REGIONAL GEOLOGIC BACKGROUND

Though early workers thought that strata recording Neoproterozoic and early Cambrian rifting of western Laurentia were missing in central Idaho across the Ordovician-on-Mesoproterozoic "Lemhi arch" unconformity (Umpleby, 1917; Ross, 1934; Scholten, 1957; Ruppel, 1986; Poole and others, 1992), recent work has demonstrated that rocks of this age are indeed present (Lund, 2004; Lund and others, 2003, 2010; Stewart and others, 2016; Brennan and others, 2020a). The Lemhi arch unconformity occurs near the Idaho–Montana border and into east-central Idaho, where recent work corroborates earlier work that Neoproterozoic and Cambrian rocks are missing (e.g., Link and others, 2017; Brennan and others, 2020a; Milton, 2020). However, on the presumed southern and western margin of the Lemhi arch, the post-Belt Supergroup, sub-Middle Ordovician, Neoproterozoic, and Cambrian section thickens toward the south and southwest into central Idaho. In the southern and west-central Lemhi Range, the basal unconformity between Lower and Middle Ordovician rocks of the Summerhouse Formation and overlying Kinnikinic Quartzite cuts progressively upsection away from the Lemhi arch paleo-high toward the east and southeast such that Cambrian and Neoproterozoic rocks are preserved (McCandless, 1982; Milton, 2020); this work indicates that the locations of the southern and southwestern margins of the Lemhi arch are well-constrained in these localities.

Approximately 12 km east of Challis, Idaho, within the northern Lost River Range and Pahsimeroi Mountains, the Leaton Gulch area likely contains the transition from the edge of the Lemhi arch into the ~3-km-thick Neoproterozoic and Cambrian section present farther west near Bayhorse (Brennan and others, 2020a). Within this region, in the southern part of the Challis 1:62,500-scale quadrangle, McIntyre and Hobbs (1987), Hobbs and Hays (1990), and Hobbs and Cookro (1995) described a sequence of predominantly quartzose strata with lesser siltstone and dolostone; upper rocks are bioturbated. Regional correlations were hindered by structural complexities, and thus the rocks were assigned a Late Proterozoic to Ordovician age based upon the presence of dolostone and trace fossils in the upper part of the sequence as well as broad similarities with the Wilbert and Summerhouse Formations of Ruppel (1975) and McCandless (1982).

Subsequent workers have also investigated the enigmatic breccias and conglomerates exposed near Leaton Gulch. Carr and Link (1999) focused primarily on rocks adjacent to an unconformity and overlying breccia/conglomerate that may have been shed from the rim of a Neoproterozoic "Beaverhead" meteor impact documented near the Idaho–Montana border (McCafferty, 1995). Carr and Link (1999) and Hargraves and others (2007) both favored a meteor impact origin for some rocks near Leaton Gulch and interpreted that deeper rocks likely correlate with the Mesoproterozoic Swauger and Lawson Creek Formations (lower formation of Leaton Gulch of Carr and Link, 1999)—interpreted to be part of the Lemhi subbasin Belt Supergroup—which were thought to be overlain in unconformity by Neoproterozoic rocks of the Wilbert Formation (upper formation of Leaton Gulch of Carr and Link, 1999). Elsewhere, generally finer-grained Lawson Creek Formation rocks gradationally overlie coarser-grained quartzites of the Swauger Formation (Hobbs, 1980). To explain the general observation at Leaton Gulch that Swauger Formation rocks sit structurally above the Lawson Creek Formation, Hargraves and others (2007) everywhere interpreted a thrust fault to separate the units. DZ U-Pb results were previously published for one sample (151PL02) from Carr and Link's (1999) upper formation of Leaton Gulch; these rocks yielded a distinctive ~500 Ma age peak, which occurs in latest Cambrian sandstones throughout the northern Rocky Mountains (Link and others, 2017).

Recent work on the rocks near Leaton Gulch was initiated by Pearson, Link, and students. Montoya (2019), as a part of an MS thesis project at Idaho State University, conducted 1:24,000-scale structural mapping of a roughly 5 by 2 km region between Leaton and Pennal gulches, focused only on rocks beneath the Eocene Challis Volcanic Group. Her primary goal was to better define the age of rocks and structural style of Mesozoic shortening along her regional-scale structural transect. In addition to her mapping, Montoya (2019) created a schematic stratigraphic column of Leaton Gulch rocks (expanded in fig. 2). Based upon the dominantly fluvial facies represented by the units, their low metamorphic grade, the presence of trace fossils in the upper section, and the coarser grain size of the majority of the rocks compared to Belt stratigraphy, she favored a predominantly Neoproterozoic to Cambrian age of the rocks. This interpretation recognized similarities with McCandless' (1982) descriptions of the Neoproterozoic–Cambrian Wilbert, and Cambro-Ordovician Summerhouse and Tyler Peak Formations described in the southern Lemhi Range. Montoya (2019) also investigated the hypothesized thrust fault of Hargraves and others (2007) but found no substantive evidence of thrusting and thus favored a stratigraphic contact.

New mapping in the Bayhorse (Brennan and others, 2020b) and Clayton (Krohe and others, 2020) quadrangles—approximately 15–30 km to the southwest—as well as U-Pb geochronology (Brennan and others, 2020a) has documented the presence of a >3-km-thick Neoproterozoic to Cambrian stratigraphic section in the region. In the context of this recent work and preliminary work in the Leaton Gulch area that suggests a range of ages (from Mesoproterozoic to Cambrian) for the strata in the area (McIntyre and Hobbs, 1987; Hobbs and Hays, 1990; Carr and Link, 1999; Hargraves and others, 2007; Montoya, 2019),

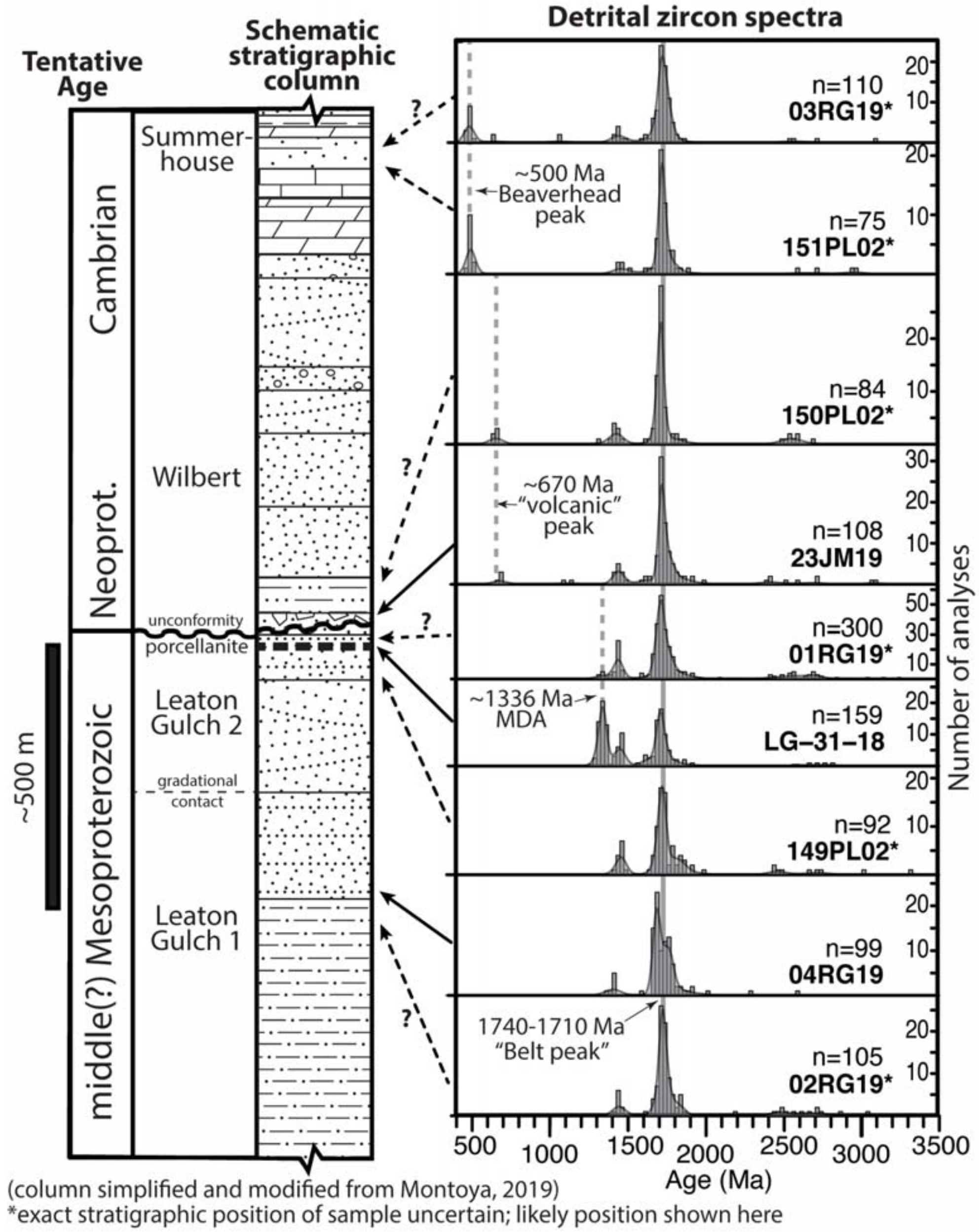

Figure 2. Schematic stratigraphic column modified from Montoya (2019). Kernel Density Estimates (KDEs) of DZ results from the Leaton Gulch area in the context of the stratigraphic column. KDEs and histograms have 25 Ma bandwidths. Samples collected in the context of the modified schematic stratigraphic section of Montoya (2019) are labeled as such; other samples were assigned a tentative stratigraphic position based upon field observations and DZ age spectra.

we collected samples of sandstones for detrital zircon U-Pb geochronology to aid in regional correlations and evaluate the provenance of these sandstones.

METHODS

A total of nine samples were collected from McIntyre and Hobbs' (1987) "Ordovician(?) to Proterozoic(?)" Formation of Leaton Gulch for U-Pb detrital zircon geochronology. Several samples were collected in the context of Montoya's (2019) schematic stratigraphic column (figs. 2, 3). The mineral separation process was undertaken at Idaho State University using standard crushing techniques. U-Pb analysis was completed at the Arizona LaserChron Center at the University of Arizona by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICPMS). $^{207}Pb/^{206}Pb$ ratios are reported for ages >900 Ma and $^{206}Pb/^{238}U$ ages are reported for ages <900 Ma. Individual analyses that were more than 10% discordant were excluded from the results and not used in subsequent interpretations of U-Pb ages. For samples 149PL02 and 150PL02, U-Pb data were acquired using a Nu High-Resolution multi-collector ICPMS and Photon Machines Analyte G2 laser according to protocols described in Gehrels and Pecha (2014). For samples

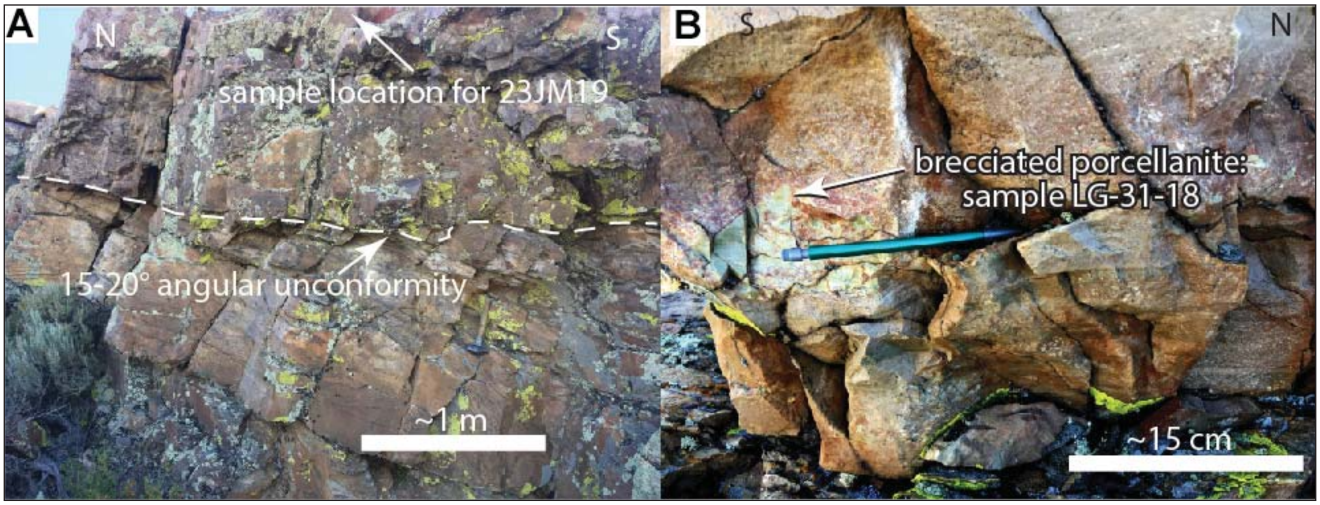

Figure 3. Field photos of (A) the angular unconformity hypothesized to separate underlying, ~1336 Ma and younger, post-Belt Supergroup rocks from overlying Neoproterozoic to Ordovician strata and (B) the brecciated green porcellanite (sample LG-31-18) that yields a strong ca. 1336 Ma U-Pb zircon age peak.

23JM19, 1RG19, 2RG19, 3RG19, and 4RG19, U-Pb data were acquired using an Element 2 single-collector high-resolution ICPMS and Photon Machines Analyte G2 laser (Pullen and others, 2018). For sample LG-31-18, initial analyses were conducted using the Nu ICPMS and subsequent analyses were conducted with the Element 2 ICPMS. For all samples, zircons were ablated with the laser using a spot diameter of 20–35 µm and samples were analyzed using standard-sample bracketing where a known standard was analyzed for every five unknowns.

RESULTS AND INTERPRETATIONS

Building upon the recent work by Montoya (2019), our preliminary results suggest that the Leaton Gulch area exposes a unique section of sedimentary rocks in the northern Rockies. All sampled rocks contain distinctive ca. 1720 and 1440 Ma age populations (fig. 2) that are statistically indistinguishable from Lemhi subbasin rocks of the Belt Supergroup. However, an interbedded green porcellanite also contains a robust, ca. 1336 Ma age population (n = 55; figs. 2–4). Given the abundance of "young" ages, which appear to be restricted in the stratigraphic section, we interpret this porcellanite as a reworked airfall tuff. This age population is >30 m.y. younger than the youngest maximum depositional ages (MDAs) constrained for Belt Supergroup strata reported by other workers (Link and others, 2007, 2016; Aleinikoff and others, 2012). The similarities with recent results reported by Box and others (2020) and Brennan (in review) suggest a tentative correlation to post-Belt Supergroup rocks of the Deer Trail Group of northeastern Washington.

These post-Belt, Mesoproterozoic rocks are overlain across a 15–20° angular unconformity by basal sandstones (figs. 2, 3) that contain a ca. 670 Ma DZ age population (samples 23JM19 and 150PL02) that is characteristic of Neoproterozoic sandstones near Bayhorse and Clayton. Our bracketed age (<1336 Ma and likely >670 Ma) for the 15–20° angular unconformity thus suggests that this tilting occurred prior to deposition of the Neoproterozoic rift and passive margin assemblage at this locality. However, there are some important contrasts between sandstones with ca. 670 Ma DZ age peaks at Bayhorse compared to at Leaton Gulch: basal sandstones at Leaton Gulch lack a large population of ca. 1100–1300 "Grenville" age DZs that are characteristic of similar rocks near Bayhorse and instead contain the distinctive ca. 1720 and 1440 Ma age peaks that are characteristic of Lemhi Group and overlying Apple Creek Formation strata (cf. Link

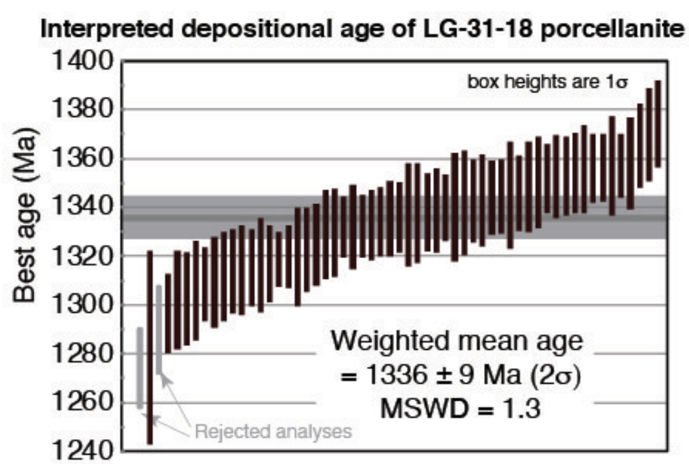

Figure 4. Weighted mean plot of young population of U-Pb zircon dates for porcellanite sample LG-31-18. MSWD, Mean square of weighted deviations.

and others, 2016). We thus interpret that these grains were recycled during early erosion of the Lemhi arch, prior to and during deposition of basal Neoproterozoic sandstones overlying the unconformity near Leaton Gulch. One new sample from upper sandstones near Leaton Gulch (sample 03RG19) yielded distinctive ca. 500 Ma DZs that is similar to Link and others' (2017) nearby sample 151PL02; coupled with mapped Middle Ordovician Kinnikinic Quartzite in the region, this suggests that a full range of Neoproterozoic, Cambrian, and Ordovician sedimentary rocks are exposed in this region (fig. 2).

One significant remaining problem that we plan to investigate with ongoing and future work is whether deeper strata exposed at Leaton Gulch (Montoya, 2019's Leaton Gulch units 1 and 2; fig. 2) are correlative to strata of parts of the Lawson Creek and Apple Creek Formations or instead overlie those rocks. Hobbs (1980) described the type section of the Lawson Creek Formation ~10 km east of our eastern sample localities. Rocks interpreted to correlate with the Lawson Creek Formation in the northern Lemhi Range gradationally overlie the medium-grained and relatively distinctive Swauger Formation and are overlain by the Apple Creek Formation (Burmester and others, 2016). Hobbs' (1980) description of the Lawson Creek Formation, which is strikingly red/purple and lithologically more heterogeneous (ranges from medium-grained sandstone to siltstone and shale with at least two intervals of apple green porcellanite) than many Belt Supergroup units, matches Montoya's (2019) and our preliminary investigation of the rocks. Near Leaton Gulch, these rocks are stratigraphically below the ca. 1336 Ma green porcellanite near Leaton Gulch. If these rocks are correlative with the Lawson Creek Formation, then this suggests that up to 5 km of rocks considered to be part of the Belt Supergroup succession (Burmester and others, 2016) are in fact >30 m.y. younger than previously thought. This is a similar problem as the presence of possibly upper Belt Supergroup rocks of the Garnet Range Formation (e.g., Kidder, 1992; Ross and Villeneuve, 2003) and Deer Trail Group (e.g., Whipple and Miller, 1988; Box and others, 2020) rocks in western Montana and northeastern Washington, respectively, which contrast in depositional environment (e.g., Winston and Link, 1993) and yield limited geochronologic data suggesting post-Belt Supergroup ages.

CONCLUSIONS

Taken together and in the context of Montoya's (2019) recent mapping, our preliminary U-Pb zircon results suggest that the Leaton Gulch region contains rare preservation of post-Belt Supergroup sedimentary rocks in the northern Rockies. All samples contain ca. 1720 and 1440 Ma U-Pb zircon age populations that are characteristic of Lemhi subbasin rocks of the Belt Supergroup. However, a green, interbedded porcellanite yielded a robust, ca. 1336 Ma U-Pb zircon population that indicates some of these rocks are younger than the Belt Supergroup. These rocks are, in turn, truncated by a 15–20° angular unconformity, which is overlain by a relatively thin section of rocks that we tentatively assign as Neoproterozoic to Ordovician in age (Wilbert and Summerhouse Formations). These rocks likely define the western flank of the latest Cambrian and Early Ordovician Lemhi arch. We hope that ongoing and future work on these rocks will better define the provenance and depositional setting of the enigmatic interval of geologic time that followed Belt Basin deposition and pre-dated Neoproterozoic and Cambrian rift and early passive margin sedimentary rocks in the northern Rocky Mountains.

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REFERENCES

Aleinikoff, J.N., Slack, J.F., Lund, K., Evans, K.V., Fanning, C.M., Mazdab, F.K., Wooden, J.L., and Pillers, R.M., 2012, Constraints on the timing of Co-Cu±Au mineralization in the Blackbird district, Idaho, using SHRIMP U-Pb ages of monazite and xenotime plus zircon ages of related Mesoproterozoic orthogneisses and metasedimentary rocks: Economic Geology, v. 107, no. 6, p. 1143–1175.

Anderson, H.E., and Davis, D.W., 1995, U–Pb geochronology of the Moyie sills, Purcell Supergroup, southeastern British Columbia: implications for the Mesoproterozoic geological history of the Purcell (Belt) basin: Canadian Journal of Earth Sciences, v. 32, no. 8, p. 1180–1193, doi: 10.1139/e95-097.

Aronoff, R.F., Andronicos, C.L., Vervoort, J.D., and Hunter, R.A., 2016, Redefining the metamorphic history of the oldest rocks in the southern Rocky Mountains: Geological Society of America Bulletin, v. 128, no. 7–8, p. 1207–1227.

Box, S.E., Pritchard, C.J., Stephens, T.S., and O'Sullivan, P.B., 2020, Between the supercontinents: Mesoproterozoic Deer Trail Group, an intermediate age unit between the Mesoproterozoic Belt–Purcell Supergroup and the Neoproterozoic Windermere Supergroup in northeastern Washington, USA: Canadian Journal of Earth Sciences, v. 41, no. 5, p. 1–17, doi: 10.1139/cjes-2019-0188.

Bookstrom, A.A., Box, S.E., Cossette, P.M., Frost, T.P., Gillerman, V.S., King, G.R., and Zirakparvar, N.A., 2016, Geologic history of the Blackbird Co-Cu district in the Lemhi subbasin of the Belt–Purcell Basin, *in* MacLean, J.S., and Sears, J.W., eds., Belt Basin: Window to Mesoproterozoic Earth: Geological Society of America Special Paper, v. 522, doi: 10.1130/2016.2522(08).

Brennan, D.T., Pearson, D.M., Link, P.K., and Chamberlain, K.R., 2020a, Neoproterozoic Windermere Supergroup near Bayhorse, Idaho: Late-stage Rodinian rifting was deflected west around the Belt basin: Tectonics, v. 39, p. 1–27, doi: 10.1029/2020TC006145.

Brennan, D.T., Pearson, D.M., and Link, P.K., 2020b, Geologic map of the Bayhorse anticline, Custer County, Idaho: Idaho Geological Survey Technical Report #T-20-01, scale 1:24,000.

Brennan, D.T., Li, Z.-X., Rankenburg, K., Evans, N., Link, P.K., Nordsvan, A.R., Kirkland, C.L., Mahoney, J.B., Johnson, T., and McDonald, B.J., 2021, Recalibrating Rodinian rifting in the northwestern United States: Geology, doi: 10.1130/G48435.1.

Brennan, D.T., Pearson, D.M., Link, P.K., and Milton, J., in review, Connecting the northern sector of the U.S. western Laurentian rift margin: An emerging Neoproterozoic to early Paleozoic tectono-stratigraphic framework for central Idaho: submitted to GSA Memoir.

Burmester, R.F., Lonn, J.D., Lewis, R.S., and McFaddan, M.D., 2016, Stratigraphy of the Lemhi subbasin of the Belt Supergroup, *in* MacLean, J.S., and Sears, J.W., Belt Basin: Window to Mesoproterozoic Earth: Geological Society of America Special Paper, v. 522, p. 121–137, doi: 10.1130/2016.2522(05).

Carr, J., and Link, P.K., 1999, Neoproterozoic conglomerate and breccia in the formation of Leaton Gulch, Grouse Peak, northern Lost River Range, Idaho: Relation to Beaverhead impact structure, *in* Hughes, S.S., and Thackray, G.D., eds., Guidebook to the Geology of Eastern Idaho: Idaho Museum of Natural History, p. 21–29.

Daniel, C.G., Pfeifer, L.S., Jones, J.V. III, and McFarlane, C.M., 2013, Detrital zircon evidence for non-Laurentian provenance, Mesoproterozoic (ca. 1490–1450 Ma) deposition and orogenesis in a reconstructed orogenic belt, northern New Mexico, USA: Defining the Picuris orogeny: Geological Society of America Bulletin, v. 125, no. 9–10, p. 1423–1441.

Deiss, C., 1935, Cambrian–Algonkian unconformity in western Montana: Geological Society of America Bulletin, v. 46, no. 1, p. 95–124.

Doughty, P.T., and Chamberlain, K.R., 1996, Salmon River Arch revisited: New evidence for 1370 Ma rifting near the end of deposition in the Middle Proterozoic Belt basin: Canadian Journal of Earth Sciences, v. 33, no. 7, p. 1037–1052.

Doughty, P.T., and Chamberlain, K.R., 2008, Protolith age and timing of Precambrian magmatic and metamorphic events in the Priest River complex, northern Rockies: Canadian Journal of Earth Sciences, v. 45, no. 1, p. 99–116, doi: 10.1139/E07-067.

Evans, J.G., 1987, Geology of the Stensgar Mountain quadrangle, Stevens County, Washington: U.S. Geological Survey Bulletin, v. 1679, p. 1–30.

Evans, K.V., and Zartman, R.E., 1990, U-Th-Pb and Rb-Sr geochronology of middle Proterozoic granite and augen gneiss, Salmon River Mountains, east-central Idaho: Geological Society of America Bulletin, v. 102, no. 1, p. 63–73.

Gehrels, G., and Pecha, M., 2014, Detrital zircon U-Pb geochronology and Hf isotope geochemistry of Paleozoic and Triassic passive margin strata of western North America: Geosphere, v. 10, p. 49–65, doi: 10.1130/GES00889.1.

Gower, C.F., 1996, The evolution of the Grenville Province in eastern Labrador, Canada: Geological Society, London, Special Publications, v. 112, no. 1, p. 197–218.

Hargraves, R.B., Ruppel, E.T., and Gephart, J.W., 2007, The Leaton Gulch breccia in east-central Idaho, U.S.A., and its relation to the Beaverhead meteorite impact: Special Publication SEPM, p. 167–174, doi: 10.2110/pec.07.86.0167.

Hobbs, S.W., 1980, The Lawson Creek Formation of Middle Proterozoic age in east-central Idaho: U.S. Geological Survey Bulletin, v. 1482-E.

Hobbs, S.W., and Cookro, T.M., 1995, Proterozoic terrane, *in* Fisher, F.S., and Johnson, K.M., eds., Geology and Mineral Resource Assessment of the Challis 1° x 2° Quadrangle, Idaho: U.S. Geological Survey Professional Paper, v. 1525, no. 4, p. 12–17, doi: 10.1130/0091-7613(1989)017<0324:LPTJSM>2.3.CO;2.

Hobbs, S.W., and Hays, W.H., 1990, Ordovician and older rocks of the Bayhorse area, Custer County, Idaho: U.S. Geological Survey Bulletin, v. 1891, p. 40.

Kidder, D.L., 1992, Stratigraphy and sedimentology of the Libby Formation, Belt Supergroup (Middle Proterozoic) of Montana and Idaho, U.S.A.: Contributions to Geology, University of Wyoming, v. 29, p. 119–131.

Kirscher, U., Mitchell, R.N., Liu, Y., Nordsvan, A.R., Cox, G.M., Pisarevsky, S.A., Wang, C., Wu, L., Murphy, J.B., and Li, Z.-X., 2020, Paleomagnetic constraints on the duration of the Australia–Laurentia connection in the core of the Nuna supercontinent: Geology, v. 49, no. 2, p. 174–179.

Krohe, N., Brennan, D.T., Link, P.K., Pearson, D.M., and Armstrong, T., 2020, Geologic map of the southern portion of the Clayton quadrangle, Custer County, Idaho: Idaho Geological Survey Technical Report #T-20-02, scale 1:24,000.

Link, P.K., Fanning, C.M., Lund, K.I., and Aleinikoff, J.N., 2007, Detrital-zircon populations and provenance of Mesoproterozoic strata of east-central Idaho, USA: Correlation with the Belt Supergroup of southwest Montana: Special Publication SEPM, v. 86, p. 101.

Link, P.K., Stewart, E.D., Steel, T., Sherwin, J.-A., Hess, L., and McDonald, C., 2016, Detrital zircons in the Mesoproterozoic upper Belt Supergroup in the Pioneer, Beaverhead, and Lemhi Ranges, Montana and Idaho: The Big White arc, *in* MacLean, J.S., and Sears, J.W., eds., Belt Basin: Window to Mesoproterozoic Earth: Geological Society of America Special Paper, v. 522, p. 163–183, doi: 10.1130/2016.2522(07).

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, p. 1–17, doi: 10.1130/L671.1.

Lonn, J.D., Burmester, R.F., Lewis, R.S., and McFadden, M.D., 2020, The Mesoproterozoic Belt Supergroup, *in* Geology of Montana, v. 1, Geologic History: Montana Bureau of Mines and Geology Special Publication 122, 38 p.

Lund, K., 2004, Geology of the Payette National Forest and vicinity, west-central Idaho: U.S. Geological Survey Professional Paper 1666.

Lund, K., Aleinikoff, J.N., Evans, K.V., and Fanning, C.M., 2003, SHRIMP U-Pb geochronology of Neoproterozoic Windermere Supergroup, central Idaho: Implications for rifting of western Laurentia and synchroneity of Sturtian glacial deposits: Geological Society of America Bulletin, v. 115, no. 3, p. 349–372, doi: 10.1130/0016-7606(2003)115<0349:SUPGON>2.0.CO;2.

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, no. 3-4, p. 430–453, doi: 10.1130/B26565.1.

McCafferty, A.E., 1995, Assessing the presence of a buried meteor impact crater using geophysical data, south-central Idaho: M.S. Thesis, Colorado School of Mines, 88 p.

McCandless, D.O., 1982, A reevaluation of Cambrian through Middle Ordovician stratigraphy of the southern Lemhi Range: M.S. Thesis, Pennsylvania State University, 159 p.

McIntyre, D.H., and Hobbs, S.W., 1987, Geologic map of the Challis quadrangle, Custer and Lemhi Counties, Idaho: U.S. Geological Survey Geologic Quadrangle Map GQ-1599, scale 1:62,500.

Medig, K.P.R., Thorkelson, D.J., Davis, W.J., Rainbird, R.H., Gibson, H.D., Turner, E.C., and Marshall, D.D., 2014, Pinning northeastern Australia to northwestern Laurentia in the Mesoproterozoic: Precambrian Research, v. 249, p. 88–99, doi: 10.1016/j.precamres.2014.04.018.

Miller, F.K., and Whipple, J.W., 1989, The Deer Trail Group: Is it part of the Belt Supergroup: Geologic guidebook for Washington and adjacent areas: Washington Division of Geology and Earth Resources Information Circular, v. 86, p. 1–21.

Milton, J., 2020, Geologic mapping, stratigraphy, and detrital zircon geochronology of the southeastern Borah Peak horst, Custer County, Idaho: Age reassignment and correlation of Neoproterozoic to Lower Paleozoic: M.S. Thesis, Idaho State University, 131 p., 1 Plate.

Montoya, L.M., 2019, Investigation of structural style within the Sevier fold-thrust belt along the southwestern boundary of the Lemhi arch, central Idaho[M.S. Thesis]: Pocatello, ID, Idaho State University, 80 p., 5 plates.

Mosher, S., 1998, Tectonic evolution of the southern Laurentian Grenville orogenic belt: Geological Society of America Bulletin, v. 110, no. 11, p. 1357–1375.

Poole, F.G., Stewart, J.H., Palmer, A.R., Sandberg, C.A., Madrid, R.J., Ross, R.J., Jr., Hintze, L.F., Miller, M.M., and Wrucke, C.T., 1992, Latest Precambrian to latest Devonian time; Development of a continental margin, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: The Geology of North America, v. G-3, no. 2, p. 9–56.

Pullen, A., Mejia, M.I., Gehrels, G.E., Giesler, D., and Pecha, M., 2018, Optimization of a laser ablation-single collector-inductively coupled plasma-mass spectrometer (Thermo Element 2) for accurate, precise, and efficient zircon U-Th-Pb geochronology: Geochemistry Geophysics Geosystems, v. 19, no. 10, p. 3689–3705, doi: 10.1029/2018GC007889.

Ross, C.P., 1934, Correlation and interpretation of Paleozoic stratigraphy in south-central Idaho: Geological Society of America Bulletin, v. 45, no. 5, p. 937–1000, doi: 10.1130/GSAB-45-937.

Ross, G.M., and Villeneuve, M., 2003, Provenance of the Mesoproterozoic (1.45 Ga) Belt basin (western North America): Another piece in the pre-Rodinia paleogeographic puzzle: Geological Society of America Bulletin, v. 115, no. 10, p. 1191–1217.

Ruppel, E.T., 1975, Precambrian Y sedimentary rocks in east-central Idaho: U.S. Geological Survey Professional Paper, v. 889-A, p. 1–42.

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

Scholten, R., 1957, Paleozoic evolution of the geosynclinal margin north of the Snake River Plain, Idaho–Montana: Geological Society of America Bulletin, v. 68, no. 2, p. 151–170, doi: 10.1130/0016-7606(1957)68[151:PEOTGM]2.0.CO;2.

Sears, J.W., and Chamberlain, K.R., 1998, Structural and U-Pb geochronological evidence for 1.47 Ga rifting in the Belt basin, western Montana: Canadian Journal of Earth Sciences, v. 35, no. 4, p. 467–475, doi: 10.1139/e97-121.

Sloss, L.L., 1988, Tectonic evolution of the craton in Phanerozoic time, *in* Sloss, L.L., ed., Sedimentary Cover—North American craton: The Geology of North America, v. D-2, p. 25–51.

Stewart, D.E., Stewart, E.D., Lewis, R.S., Weppner, K.N., and Isakson, V.H., 2016, Geologic map of the Stibnite quadrangle, Valley County, Idaho: Idaho Geological Survey Geologic Map, v. 51, scale 1:24,000.

Stewart, J.H., 1972, Initial deposits in the Cordilleran geosyncline: Evidence of a late Precambrian (<850 m.y.) continental separation: Geological Society of America Bulletin, v. 83, no. 5, p. 1345–1360, doi: 10.1130/0016-7606(1972)83[1345:IDITCG]2.0.CO;2.

Umpleby, J.B., 1917, Geology and ore deposits of the Mackay region, Idaho: U.S. Geological Survey Professional Paper, v. 97, p. 129 p.

Whitmeyer, S.J., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, doi: 10.1130/GES00055.S1.

Winston, D., and Link, P.K., 1993, Middle Proterozoic rocks of Montana, Idaho, and eastern Washington: the Belt Supergroup, *in* Middle and Late Proterozoic stratified rocks of the western U.S. Cordillera, Colorado Plateau, and Basin and Range province, Link, P.K., Christie-Blick, N., Devlin, W.J., Elston, D.P., Horodyski, R.J., Levy, M., Miller, J.M.G., Pearson, R.C., Prave, A., Stewart, J.H., Winston, D., Wright, L.A., and Wrucke, C.T., *in* Reed, J.C.J., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R. eds., The Geology of North America, Precambrian: Conterminous U.S, v C-2, ch. 6, p. 487–517.