THE GEOLOGICAL SOCIETY OF AMERICA®

500–490 Ma detrital zircons in Upper Cambrian Worm Creek and correlative sandstones, Idaho, Montana, and Wyoming: Magmatism and tectonism within the passive margin

Paul K. Link[1], Mary Katherine Todt[1], David M. Pearson[1], and Robert C. Thomas[2]
[1]DEPARTMENT OF GEOSCIENCES, IDAHO STATE UNIVERSITY, 921 S. 8TH AVENUE, POCATELLO, IDAHO 83209, USA
[2]DEPARTMENT OF ENVIRONMENTAL SCIENCES, UNIVERSITY OF MONTANA WESTERN, 710 S. ATLANTIC STREET, DILLON, MONTANA 59725, USA

ABSTRACT

Upper Cambrian feldspathic sandstones deposited across southeast Idaho, Montana, and Wyoming (USA) during the Sauk II-Sauk III regression boundary contain distinctive 500–490 Ma detrital zircon grains, derived from Late Cambrian plutons in the Lemhi arch of east-central Idaho. The Worm Creek Quartzite Member of the St. Charles Formation in the Paris plate of the southeast Idaho thrust belt contains as much as 320 m of feldspathic fine-grained sandstone within a thick section of carbonate rocks. The near-unimodal age of hundreds of detrital zircons from 8 samples of the Worm Creek is 497 Ma. This age and the initial εHf values from these detrital zircons (εHf of –8.0 ± 1.9 to 5.4 ± 1.2) overlap the age and isotopic composition of the Deep Creek and Beaverhead plutons intruded into the Lemhi arch (εHf of –6.3 ± 1.1 to 2.7 ± 1.4). This suggests rapid unroofing of the hypabyssal alkalic plutons, which were the primary source for the sandstones. In the plutons, intermediate initial εHf values are neither juvenile nor evolved, suggesting mixing with a Mesoproterozoic component. A 493–488 Ma detrital zircon age peak is also found in Upper Cambrian sandstones (from the Sauk II-III boundary) in the Wind River Canyon on the Wyoming craton, the Melrose area of the southwest Montana thrust belt, and the Leaton Gulch area of the central Idaho thrust belt. The detrital zircon signatures of these Upper Cambrian rocks is markedly different from that of the Lower Cambrian upper Brigham Group in southeast Idaho and the Middle Cambrian Flathead Sandstone at Teton Pass, Wyoming (1790 Ma age peak). The overlying Middle Ordovician Swan Peak and Kinnikinic Quartzites from Idaho south to Nevada contain a different detrital zircon age population, with almost all grains older than 1800 Ma and a peak at 1860 Ma.

We suggest that the Lemhi arch is a relatively unextended crustal block coincident with the northwest-trending Mesoproterozoic Lemhi subbasin of the Belt Supergroup and with ca. 1.37 Ga mafic magmatism. This magmatism strengthened the lower crust and predisposed the Lemhi arch to remain intact during extension and Neoproterozoic rifting of western Laurentia. Oblique normal faulting and subsidence along the dextral normal Snake River transfer fault produced the Late Cambrian Worm Creek basin and juxtaposed active Cambrian magmatism and exhumation with passive-margin sedimentation to the south.

LITHOSPHERE GSA Data Repository Item 2017339 https://doi.org/10.1130/L671.1

INTRODUCTION

In western North America, Neoproterozoic volcanism and siliciclastic sedimentation associated with protracted Rodinian rifting was followed by Cambrian passive margin sedimentation with deposition of thick carbonate platform strata (Bond et al., 1985; Christie-Blick and Levy, 1989; Link et al., 1993; Dickinson, 2004; Yonkee et al., 2014). South of the modern Snake River Plain, >6 km of Neoproterozoic and lower Paleozoic strata were deposited within the westward-thickening passive margin as part of the Sauk megasequence (Fig. 1; e.g., Sloss, 1963; Bond and Kominz, 1984; Bush et al., 2012). Cambrian strata are predominately carbonate rocks, but throughout the Paris plate of the southeast Idaho thrust belt, at the sequence boundary or regressive maximum of the Sauk II-Sauk III contact, feldspathic sandstones interrupt the carbonate-dominated sequence (Armstrong and Oriel, 1965).

In east-central Idaho, there are no Neoproterozoic and Cambrian passive margin strata across the Lemhi arch (Fig. 1; Sloss, 1954; Ruppel, 1986). In this area, Cambrian to Ordovician alkalic plutons of the Beaverhead magmatic belt were emplaced into Mesoproterozoic Belt Supergroup strata (Evans and Zartman, 1988; Lund et al., 2010). Because Middle Ordovician Kinnikinic Quartzite unconformably overlies the Mesoproterozoic Belt Supergroup (Fig. 1), there is no evidence of Neoproterozoic and Cambrian rift and post-rift subsidence and sedimentation.

The Transcontinental Arch, a poorly defined uplift trending northeast-southwest across the western midcontinent of North America (Sloss, 1988; Amato and Mack, 2012), is interpreted to have been uplifted in Middle Cambrian time, such that it blocked transport of Grenville-aged detrital zircon grains from eastern Laurentia to the western passive margin (Yonkee et al., 2014; Linde et al., 2014). East of the arch, in southern New Mexico, 509–504 Ma Late Cambrian detrital zircons with an interpreted proximal magmatic source are found in the Bliss Sandstone (Amato and Mack, 2012). Early and Middle Cambrian magmatism (539–528 Ma) is recognized in the southern Oklahoma aulacogen (Hogan and Gilbert; 1998). West of the Transcontinental Arch, sparse 500 ± 15 Ma diabase dikes are present

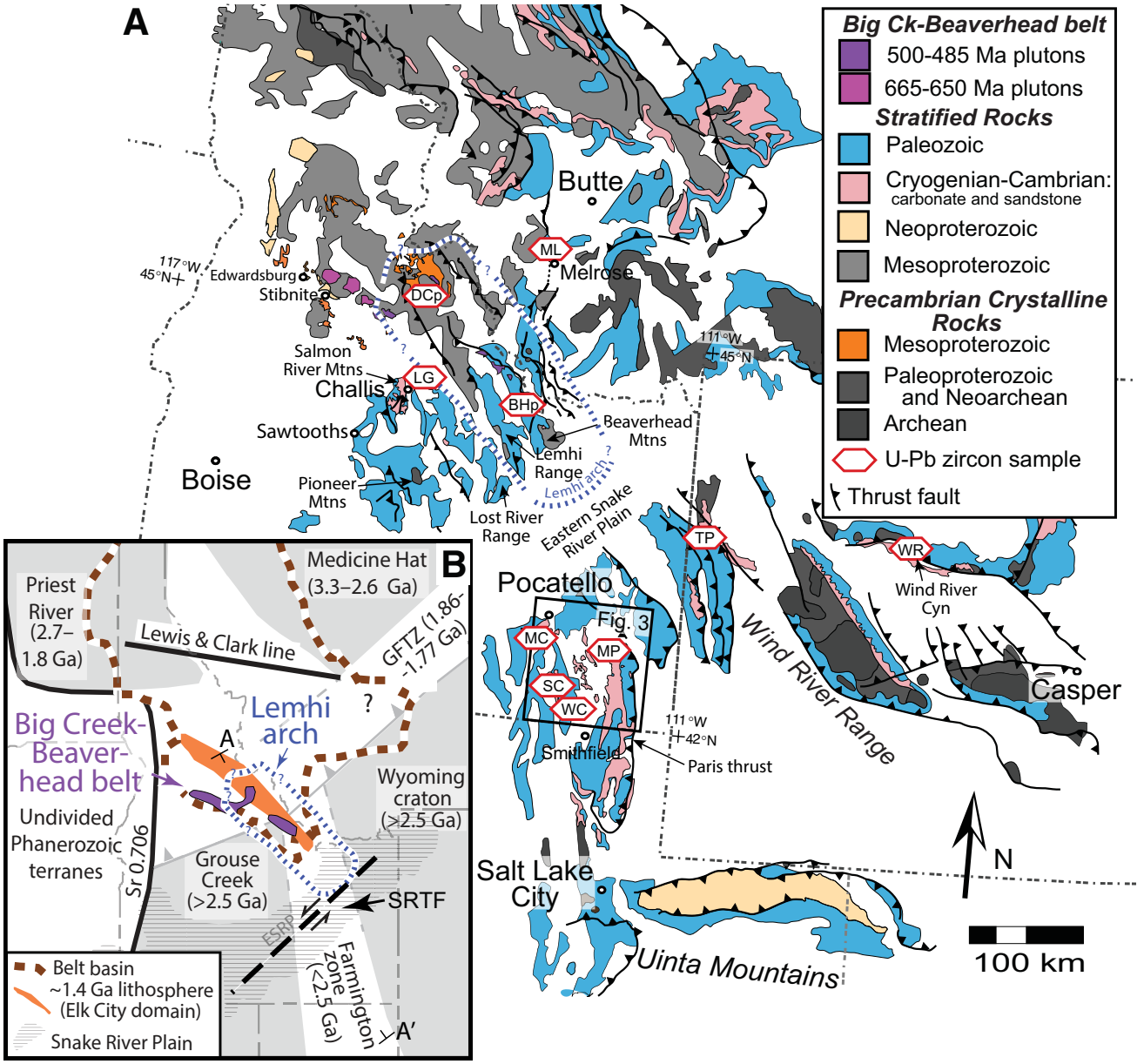

Figure 1. (A) Present-day outcrop map of the U.S. northern Rocky Mountains. Black square denotes the map extent of Figure 3. Modified from Muehlberger (1983), Vuke et al. (2007), Lund et al. (2010), and Lewis et al. (2012). Ck—Creek. U-Pb zircon sample localities (p = plutonic sample): BHp—Beaverhead pluton; DCp—Deep Creek pluton; LG—Leaton Gulch, MC—Midnight Creek; ML—Melrose; MP—McPherson Canyon; SC—Secret Canyon; TP—Teton Pass; WC—Weston Canyon; WR—Wind River Canyon. (B) Basement domains (modified from Gaschnig et al., 2013), approximate extent of the Lemhi arch (modified from Ruppel, 1986), and location of ca. 1.4 Ga plutons and isotopically delineated 1.4 Ga lithosphere (Doughty and Chamberlain, 1996; Elk City domain of Gaschnig et al., 2013). Line of cross section of Figure 11 is shown. SRTF—Snake River transfer fault (modified from Lund, 2008); GFTZ—Great Falls tectonic zone.

in west-central Colorado (Larsen et al., 1985), but such mafic rocks are zircon poor. Cambrian zircon grains have not been detected in regional studies of Paleozoic strata of the Cordillera (Gehrels and Pecha, 2014) or in sandstones from western and northwestern Canada (Hadlari et al., 2012).

Within the Upper Cambrian carbonate rocks[1] of the passive margin in southeast Idaho on the Paris thrust plate (Fig. 1), the presence of 0–320 m of feldspathic sandstone in the uppermost Cambrian Worm Creek Quartzite Member of the St. Charles Formation has been known for more than 60 yr (Armstrong and Oriel, 1965, 1982). We demonstrate that the Beaverhead belt of plutons was the primary source for coeval Worm Creek Quartzite. In this paper we refer to the Worm Creek Quartzite Member of the St. Charles Formation and underlying sandstone in the top of the Nounan Dolomite as the "Worm Creek sandstone." This link suggests that instead of a tectonically quiet subsiding margin during the latest Cambrian, intrusion and exhumation occurred within the Lemhi arch of central Idaho, and sand deposition occurred in what had been a carbonate platform in southeast Idaho. Furthermore, the coincidence of these events with the Sauk II-Sauk III regression raises questions about linkage and causality, including the possibility that uplift of the Lemhi arch contributed to the Sauk II-Sauk III lowstand. In this paper we summarize Worm Creek sandstone cyclicity and present detrital zircon analyses of uppermost Cambrian sandstones from central Idaho east to central Wyoming. We compare U-Pb ages and initial εHf isotopic compositions of these zircons to zircons from the Beaverhead and Deep Creek plutons from the Beaverhead belt of east-central Idaho (Todt and Link, 2013; Todt, 2014).

Because our samples span from the Laurentian craton on the east to the central Idaho thrust belt, these data provide a test of the Rubia ribbon continent model of Johnston (2008) and Hildebrand (2009). This model holds that the western thrust belt contains a narrow continental block exotic to Laurentia.

GEOLOGIC SETTING

South of the Snake River Plain

The breakup of Rodinia and formation of the Laurentian passive margin in Utah and Idaho south of the Snake River Plain was protracted and occurred as multiple stages (Link et al., 1993; Yonkee et al., 2014). The final stage of rifting began near 570 Ma, with true development of the Cordilleran passive margin after 550 Ma, and thick carbonate deposition concomitant with eustatic sea-level rise through the Cambrian (Bond and Kominz, 1984; Thomas, 1993; Saltzman et al., 2004).

The sandstones studied in this paper belong to the siliciclastic inner detrital belt (as opposed to the shale-rich outer detrital belt; Palmer, 1971; Myrow et al., 2012), and were deposited during a Laurentian sea-level low across the Sauk II-Sauk III boundary (Sloss, 1988). This boundary, locally an unconformity or sequence boundary, is coincident with the Steptoean positive isotopic carbon excursion (SPICE), a strong positive $\delta^{13}C$ swing in Furongian time (ca. 497–485 Ma; Fig. 2), correlated with a high in atmospheric oxygen and a punctuated increase in invertebrate complexity (Saltzman et al., 1998, 2004, 2011).

[1]Although "Lower, Early" and "Upper, Late Cambrian" are formal terms of the U.S. Geological Survey, the 1999 and subsequent versions of the *GSA Geologic Time Scale* and recommendations of the International Subcommission on Cambrian Stratigraphy (http://www.palaeontology.geo.uu.se/ISCS/ISCS_home.html) instead divide the Cambrian into 4 epochs, Terreneuvian, Epoch 2, Epoch 3, and Furongian. However, in keeping with common usage, we still use uppercase when referring to Early, Middle and Late Cambrian time and Lower, Middle and Upper Cambrian rocks. We follow the 1999 time scale and use Laurentian stage terms (Steptoean and Sunwaptian) for Cambrian division D, which includes the Worm Creek Quartzite Member of the St. Charles Formation (see Fig. 2).

Uppermost Cambrian Sandstone

In southeast Idaho, south of the Snake River Plain, >1 km of Cambrian carbonate-rich strata of the Sauk sequence records overall sea-level rise (Fig. 2; Armstrong and Oriel, 1965; Trimble and Carr, 1976). The uppermost Nounan Dolomite and overlying feldspathic Worm Creek Quartzite Member of the St. Charles Formation were deposited during pulsed regressions across the Sauk II-Sauk III boundary ca. 495 Ma (Furongian Epoch, Steptoean stage [1999 GSA Geologic Time Scale]) (Fig. 3) (Sloss, 1988; Saltzman et al., 2004; Haq and Schutter, 2008). These are manifested as four siliciclastic to carbonate cycles (Fig. 3). The Sauk II-III contact was represented by Haq and Schutter (2008) as eustatic relative sea-level falls of 25–75 m at 499 Ma and >75 m at 495 Ma.

In southeast Idaho, the rocks of concern include the uppermost Nounan Dolomite (*Crepicephalus*, *Aphelaspis*, and *Dunderbergia* trilobite zones, 498.5–494 Ma), and the Worm Creek Quartzite Member of the St. Charles Formation (*Dunderbergia* and *Elvinia* trilobite zones; 495.2–493 Ma; time scale of Gradstein et al., 2012, here and henceforth) (Fig. 2; Howell et al., 1944; Haynie, 1957; Armstrong and Oriel, 1965; Lochman-Balk, 1974; Saltzman et al., 2004; Hintze and Kowallis, 2009, fig. 25 therein). The uppermost Nounan and overlying Worm Creek Quartzite Member form four upward-fining cycles, and are henceforth referred to as the Worm Creek sandstone. On the north at Midnight Creek (MC in Fig. 1), just south of the Snake River Plain, the Worm Creek totals 320 m in thickness (Fig. 3). Only 2 cycles totaling 26 m are evident toward the southeast at Weston Canyon (WC in Fig. 1) along the Idaho-Utah border. Paleocurrents derived from planar foresets in cross-bedded sandstone in northern Utah are bimodal, trending northwest (280°) and southeast (100°) in some localities and unimodal to the east-northeast (70°) in others (R.Q. Oaks, Utah State University, 2013, written commun.).

The Nounan Dolomite thickens northward from a feather edge at the Idaho-Utah border to >150 m thick just south of the Snake River Plain (Trimble and Carr, 1976). Its upper member contains the stratigraphically lowest sandstone of cycle 1 at Weston Canyon (Gardiner, 1974).

The Worm Creek Quartzite Member of the St. Charles Formation contains three siliciclastic to carbonate cycles of fine-grained subarkosic arenite (Fig. 3). Worm Creek sandstone contains detrital potassium feldspar (photomicrographs shown in Figs. 4A–4D). X-ray diffraction study of the feldspar (Todt, 2014) shows it is microcline. The sandstones locally contain plutonic myrmekite (Fig. 4C). Volcanic glass, or its altered manifestation, is lacking. Palmer (1971) hypothesized that the feldspar was derived from the Lemhi arch. The thickest section of the Worm Creek (320 m) is near Midnight Creek in the northern Bannock Range (MC in Fig. 1; A in Fig. 3), immediately south of the Snake River Plain. There, three cycles of potassium feldspar (5%–40%) arenite to limy and dolomitic mudstone, wackestone, and packstone are present (Wakeley, 1975; Trimble and Carr, 1976). The thickest package (cycle 3 of Fig. 3) is >150 m thick. It is made up of light pink to tan, poorly sorted, very fine to coarse, trough cross-bedded limy sandstone with 10% potassium feldspar (microcline) and 90% quartz (Todt, 2014). Shallow-marine trace fossils paired with the herringbone (Fig. 5A) and trough cross-stratification are indicative of terrigenous subtidal sand shoals that pass upward to tidal flats and sublittoral lagoons (Walcott, 1908; Gardiner, 1974; Wakeley, 1975). Saltzman et al. (2004) interpreted lower shoreface environments for cycles 2 and 3 at Smithfield, Utah (Fig. 1).

Upper Cambrian strata in the northern Lost River Range, east of Challis, Idaho (Fig. 1), broadly correlative with the Worm Creek sandstone, include >25 m of the upper part of the Wilbert Formation (Fig. 2; Hargraves et al., 2007). These strata consist of trace fossil-bearing (*Skolithos*) siltstone and quartz arenite. They had previously been included in the informal formation of Leaton Gulch (McIntyre and Hobbs, 1987; Carr and Link, 1999).

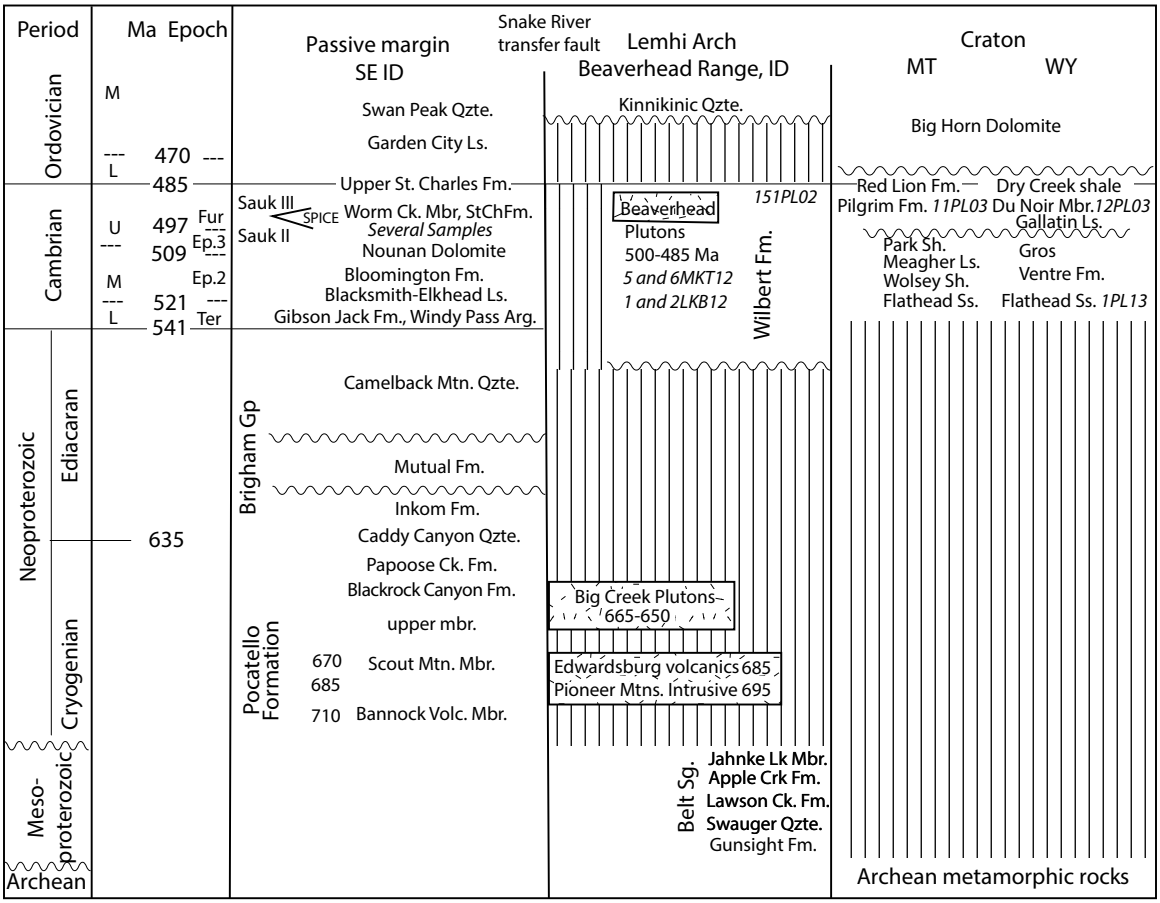

Figure 2. Correlation chart of stratigraphic relationships within the passive margin in the Paris thrust plate south of the Snake River Plain, Lemhi arch in the Beaverhead Range north of the Snake River Plain, and Montana (MT) and Wyoming (WY) craton. ID—Idaho. New samples reported in this paper are shown (data are in Figs. 5 and 10). Thin vertical lines and wavy horizontal lines are unconformities. Radiometric ages obtained from igneous zircon grains are from Lund et al. (2010) and Keeley et al. (2013). Ter—Terreneuvian, S2—series 2, S3—series 3, Fur—Furongian, SPICE—Steptoean positive isotopic carbon excursion (Saltzman et al., 1998) (ages are from the International Chronostratigraphic Chart; Cohen et al., 2013). Previous usage of Lower (L), Middle (M), and Upper (U) Cambrian is also shown. Abbreviations: StChFm.—St. Charles Formation; Ep.—Epoch; Ser.—series; Fm.—formation; Ss.—sandstone; Ls.—limestone; Mbr.—member; Qzte.—quartzite; Arg.—argillite; Sh—shale; Vol.—volcanic; Sg.—supergroup; Ck.—creek.

Upper Cambrian strata in the Wind River Canyon in central Wyoming (WR in Fig. 1) include the Du Noir Member of the Gallatin Limestone (Fig. 2). Near the top of the formation on the south-facing slope of Cottonwood Creek Canyon near the southern end of the Wind River Canyon, the Du Noir Member contains a 0.4-m-thick sandstone unit sampled for this paper. This bed is 0.6 m below the informal Dry Creek shale (Thomas, 1993). It is a white, trough cross-bedded, mature, medium-grained quartz sandstone, containing scattered abraded *Crepicephalus* Zone trilobites. The bed is thus 0.6 m below the *Marjumiid-Pterocephaliid* extinction boundary or the *Crepicephalus-Aphelaspis* zonal boundary (Thomas, 1995).

In southwest Montana, at Camp Creek near the town of Melrose (ML in Fig. 1), the upper few meters of the Upper Cambrian Pilgrim Formation (Fig. 2) contain several beds of white, trough cross-bedded, medium-grained quartz sandstone (Thomas, 2007; Thomas and Roberts, 2007). The upper sandstone, sampled for this paper, contains macerated *Crepicephalus* Zone trilobites, and is 0.3 m below the *Marjumiid-Pterocephaliid* extinction boundary or the *Crepicephalus-Aphelaspis* zonal boundary. This is just below the contact with the Upper Cambrian Red Lion Formation.

North of the Snake River Plain: The Lemhi Arch

North of the Snake River Plain in east-central Idaho is a northwest-trending region of thinned or missing Neoproterozoic to lower Paleozoic strata, the Lemhi arch (Fig. 1; Sloss, 1954; Scholten, 1957; Armstrong, 1975; Ruppel, 1986). Across much of the Lemhi arch, Middle Ordovician Kinnikinic Quartzite (James and Oaks, 1977) unconformably overlies tilted Mesoproterozoic Belt Supergroup (Fig. 2; Ross, 1947; Sloss, 1950, 1954; Lochman-Balk, 1971; Ruppel, 1986; Bush et al., 2012). On the southeastern side of the Lemhi arch in the southern Lemhi and Beaverhead Ranges, latest Neoproterozoic and Cambrian Wilbert Formation overlies the unconformity (Fig. 2; Skipp and Link, 1992). In central Idaho along the Salmon River southwest of Challis, Cambrian and Ordovician carbonate and siliciclastic rocks of the Bayhorse assemblage (Hobbs and Hays, 1990; Hobbs et al., 1991) were deposited on the downfaulted western side of the Lemhi arch (Pearson et al., 2016). Brigham Group correlative strata near Edwardsburg and Stibnite (Fig. 1) are west of the arch (Lund et al., 2003; Lewis et al., 2014).

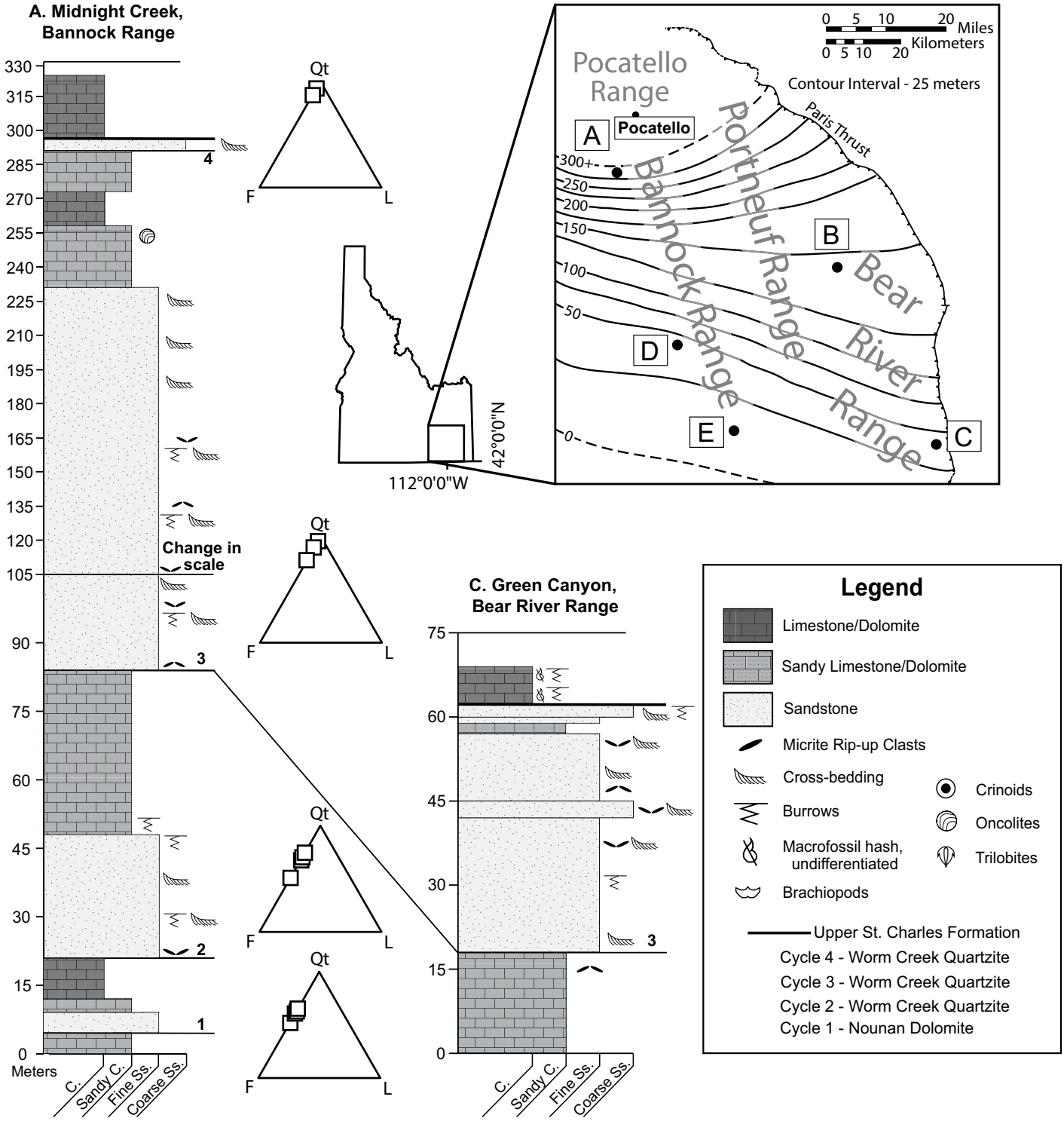

Figure 3. Location map and measured stratigraphic columns for two of seven study locations; 500 point thin section point counts for each of the four siliciclastic layers (ternary diagrams: Qt—quartz, F—almost 100% K-feldspar, L—lithics); and isopach map of the third siliciclastic layer—the main siliciclastic wedge, contour interval 25 m, throughout the Nounan–Worm Creek depositional basin, southeast Idaho. Locations were chosen from regional map of Oriel and Platt (1980). Locations of samples are shown; letters are as follows: A—Midnight Creek (1MKT12, 2MKT12, 3MKT13); B—McPherson Canyon Road (7MKT12, 8MKT12, 9MKT12); C—Green Canyon Measured Section; D—Secret Canyon (7MKT13); E—Weston Canyon (1MKT13). The thickest column, located at Midnight Creek, shows all four cycles of siliciclastic sedimentation. Notice the change in scale in the stratigraphic column of the third cycle at the Midnight Creek location.

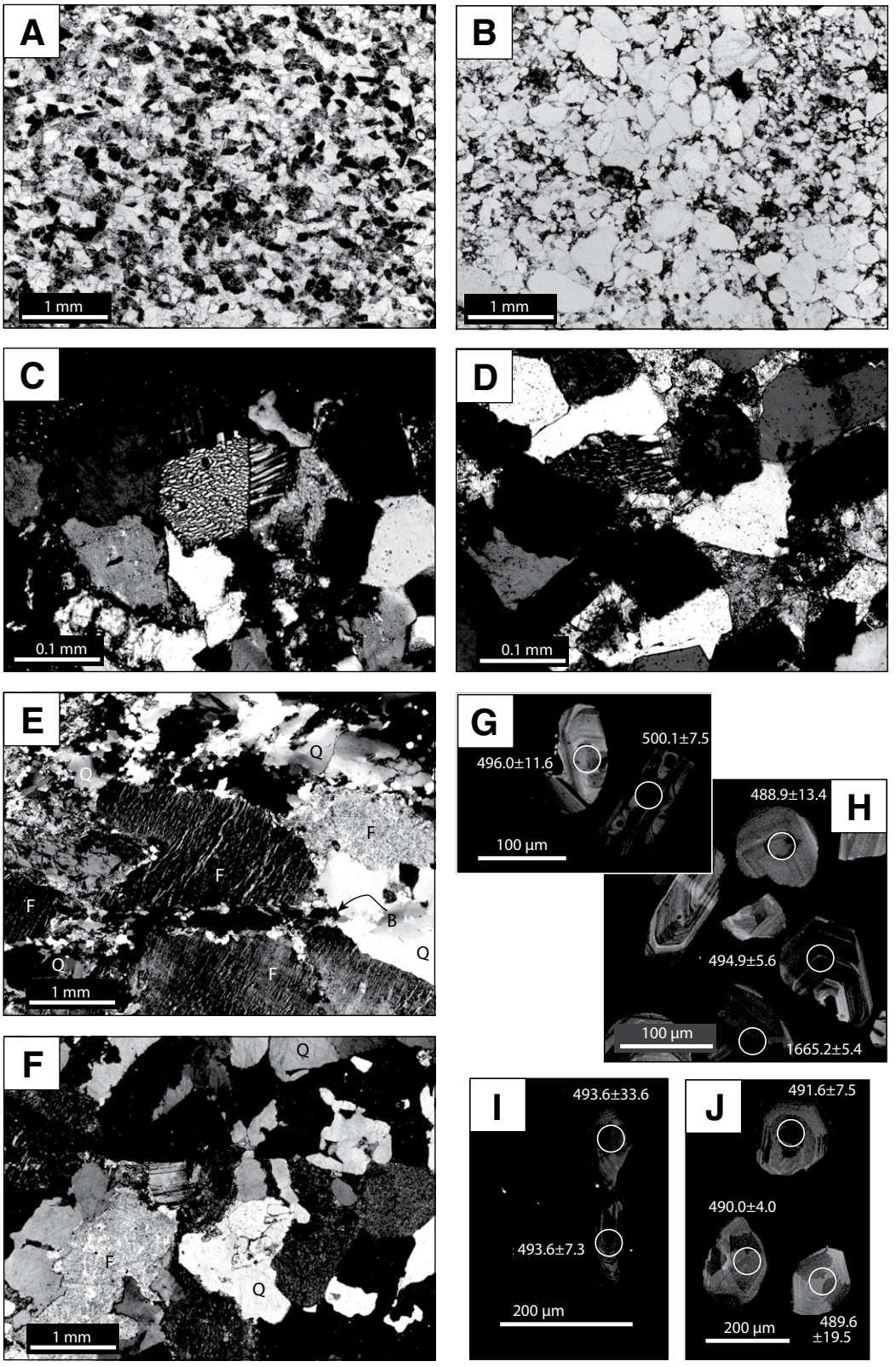

Figure 4. Thin section photomicrographs for select siliciclastic layers of the Worm Creek Quartzite, the Beaverhead pluton, and Deep Creek pluton, and cathodoluminescence (CL) images of the study detrital and igneous zircon. Mineral abbreviations: Q—quartz, F—feldspar, B—biotite. (A) Worm Creek Quartzite (01MKT12)—cycle 2 siliciclastic layer with >40% stained feldspar content (uncrossed polars). (B) Worm Creek Quartzite (02MKT12)—cycle 3 siliciclastic layer with <15% stained K-feldspar content (uncrossed polars). (C) Worm Creek Quartzite (05MKT13)—cycle 3 siliciclastic layer; large feldspar grain has perthitic texture (crossed polars). (D) Worm Creek Quartzite (07MKT12)—cycle 2 siliciclastic layer with subhedral and blobby feldspar grain shape (crossed polars). (E) Deep Creek pluton (01LKB12) (crossed polars). (F) Beaverhead pluton (05MKT12) (crossed polars). (G) Example CL image from 09MKT12 showing zircon morphologies for cycle four—Worm Creek sandstone. (H) CL image for 08MKT12, cycle three—Worm Creek sandstone. Ages of zircon grains shown in Ma. (I) CL image for Beaverhead pluton (05MKT12). (J) CL image for Deep Creek pluton (02LKB12).

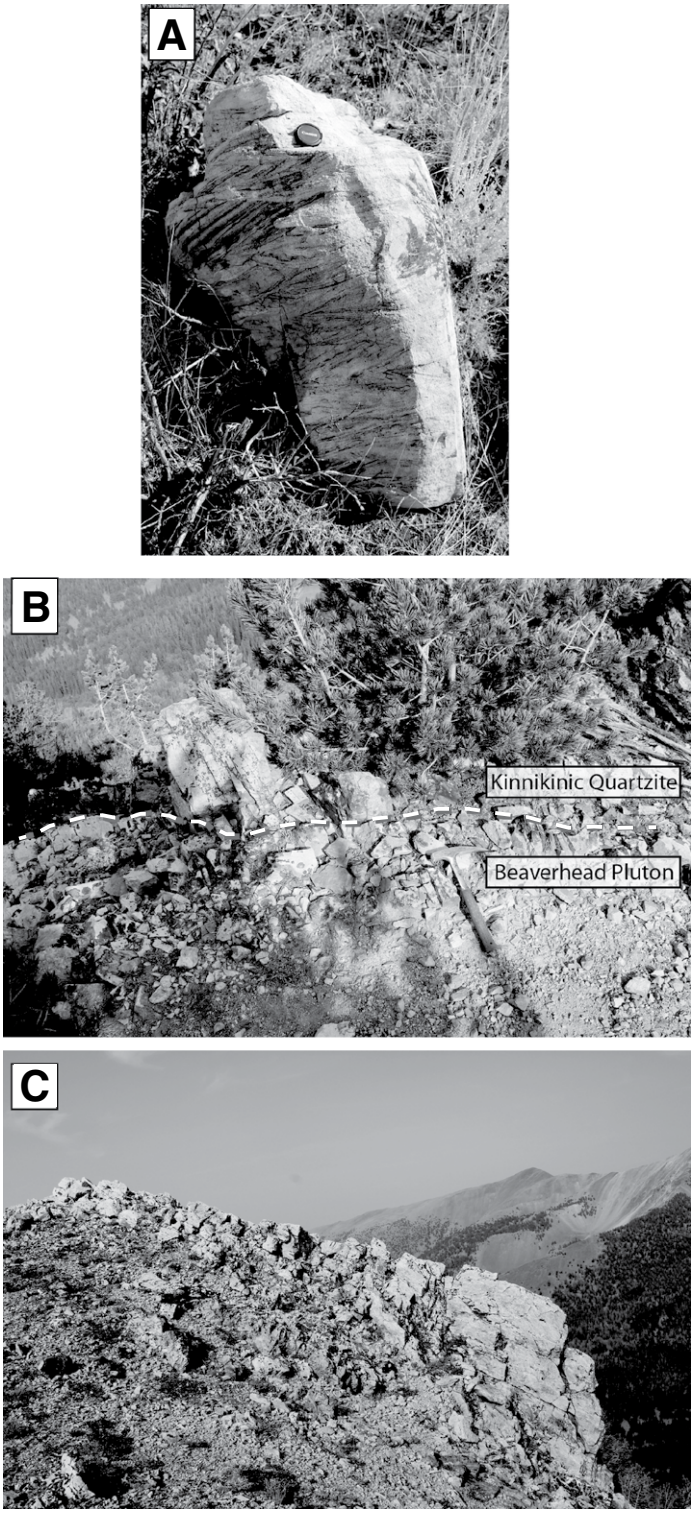

Figure 5. (A) Outcrop photograph of planar cross-bedded fine sandstone of the second siliciclastic layer—Worm Creek Quartzite, Midnight Creek location (MC in Fig. 1). Diameter of lens cap is 3 cm. (B) Outcrop photograph of the unconformable contact (dashed line) between the Late Cambrian Beaverhead pluton and the Ordovician Kinnikinic Quartzite; 18 Mile Creek, west side Beaverhead Mountains; east-central Idaho. Width of field of view is 2 m. (C) Bedded Kinnikinic Quartzite along ridge south of 18 Mile Creek, near Beaverhead pluton sample location. Photographs by M.K. Todt. Width of field of view is 100 m.

Within the Lemhi arch, the Big Creek–Beaverhead magmatic belt contains the Big Creek (665–650 Ma) and Beaverhead (500–485 Ma) hypabyssal alkalic granitoid plutons. These intruded into Mesoproterozoic upper Belt Supergroup (Fig. 1 and 2; Evans and Zartman, 1988; Lund et al., 2010; Lewis et al., 2012). Within the Beaverhead suite of plutons, the Beaverhead and Deep Creek granitoids are specific geologic units that we sampled (Evans and Zartman, 1988; Lund et al., 2010).

The mildly bimodal, alkalic nature of the Big Creek–Beaverhead belt plutons suggests that they originated as lithospheric melts intruded during progressive crustal extension (Lund et al., 2010). The two discrete magmatic pulses, at 665–650 Ma and 500–485 Ma, may have reflected recurrent extension along an inherited structural weakness (Lund, 2008). They have been correlated with initial and final rifting of western Laurentia (Yonkee et al., 2014).

The contact between the Beaverhead pluton and the Kinnikinic Quartzite is planar, but irregular, with no contact metamorphism (photos in Figs. 5B, 5C). Scholten and Ramspott (1968) interpreted this contact as intrusive. This interpretation was supported by a K-Ar age on biotite of 441 ± 15 Ma. The age is 50 m.y. younger than the U-Pb zircon age (Evans and Zartman, 1988; Lund et al., 2010). The fact that the Kinnikinic Quartzite is Middle Ordovician (470–458 Ma; James and Oaks, 1977), and thus younger than the Late Cambrian and Early Ordovician Beaverhead pluton, indicates that an intrusive contact is not possible. We interpret the contact (Fig. 5B) as an unconformity. This requires post-intrusive uplift, even if the plutons were initially hypabyssal (within a few hundred meters of the surface). This interpretation is consistent with the map relations shown by Skipp (1984).

In contrast to the dominantly Archean lithospheric framework in southwestern Montana (e.g., Foster et al., 2012; Gaschnig et al., 2013), magmas that were intruded in the region of the Lemhi arch completely lack an Archean isotopic influence. Along the Salmon River (orange polygons north of DCp in Fig. 1) is a region of 1370 Ma magmatism, interpreted to represent melting of lower Belt Supergroup strata by juvenile magma (Doughty and Chamberlain, 1996). Doughty and Chamberlain (1996) interpreted that the region is underlain by Mesoproterozoic lithosphere generated after Belt basin extension.

In the Pioneer Mountains (Fig. 1) 2.7–2.6 Ga orthogneiss is intruded by rift-related 695 Ma granitic plutons (Durk et al., 2007; Gaschnig et al., 2013; Link et al., 2017). Yates (1968) hypothesized a 350 km trans-Idaho discontinuity, extending northwest across central Idaho and east of the Pioneer Mountains, between outcrops of diamictites and rift-related volcanic rocks at Pocatello and Edwardsburg (Fig. 1). The U-Pb ages of the Wildhorse gneiss in the Pioneer Mountains obviate the concept, because Archean basement is present on both sides of the discontinuity.

Lund (2008) proposed that the Lemhi arch was part of the upper plate of an east-dipping low-angle rift fault (i.e., Lister et al., 1986), and was bounded on the south by the high-angle Snake River transfer fault (i.e., Thomas, 1977, 2014) (SRTF in Fig. 1 inset). In a lower plate setting south of the Snake River Plain, thousands of meters of rift-related and post-rift strata were deposited (Yonkee et al., 2014). A down-to-the-west pre-Ordovician normal fault was mapped along the west side of the Lemhi arch (Hansen, 2015; Hansen and Pearson, 2016). West of this fault, Neoproterozoic and Cambrian strata, not present on the Lemhi arch to the east, are recognized at Edwardsburg, Stibnite, and in the Sawtooth Mountains (Fig. 1) (Hobbs et al., 1991; Lund et al., 2003; Lewis et al., 2012, 2014; Ma et al., 2016).

Upper Cambrian Sandstones on the Wyoming Craton

To the east, on the craton (Fig. 2), Cambrian rocks of Wyoming compose a sandstone-shale-carbonate transgressive sequence punctuated by

the Sauk II–Sauk III regression (Lochman-Balk, 1971; Middleton et al., 1980; Thomas, 1994). Middle Cambrian sandstone of the Flathead Sandstone overlies Archean Wyoming province basement (Middleton et al., 1980). Detrital zircons in the middle Flathead from the Bighorn Basin in northwest Wyoming and from southwest Montana contain a unimodal 1790 Ma peak (May et al., 2013; Mahoney et al., 2015), but this age peak is muted or missing in four samples of the Flathead from the southern Beartooth Mountains in northwest Wyoming (Malone et al., 2017). The bulk of the overlying Cambrian section is carbonate, but thin sandstone (that we sampled) is present at the top of the Upper Cambrian Du Noir Member of the Gallatin Formation, representing the Sauk II–Sauk III regression.

METHODS

Zircon U-Pb and εHf Isotopic Analysis

Seven stratigraphic sections of the Worm Creek sandstone within the Paris thrust plate were measured (Todt, 2014; Fig. 3). The rocks compose four siliciclastic to carbonate cycles. Thin sections were cut and 500 points per section were counted. Triangular sandstone diagrams are shown in Figure 3. U-Pb analysis was applied to randomly selected zircons from 11 detrital samples (Fig. 6 and 7). We analyzed two zircon separates from each of the four stratigraphic cycles within the Worm Creek sandstone, plus samples from Teton Pass and Wind River Canyon, Wyoming,

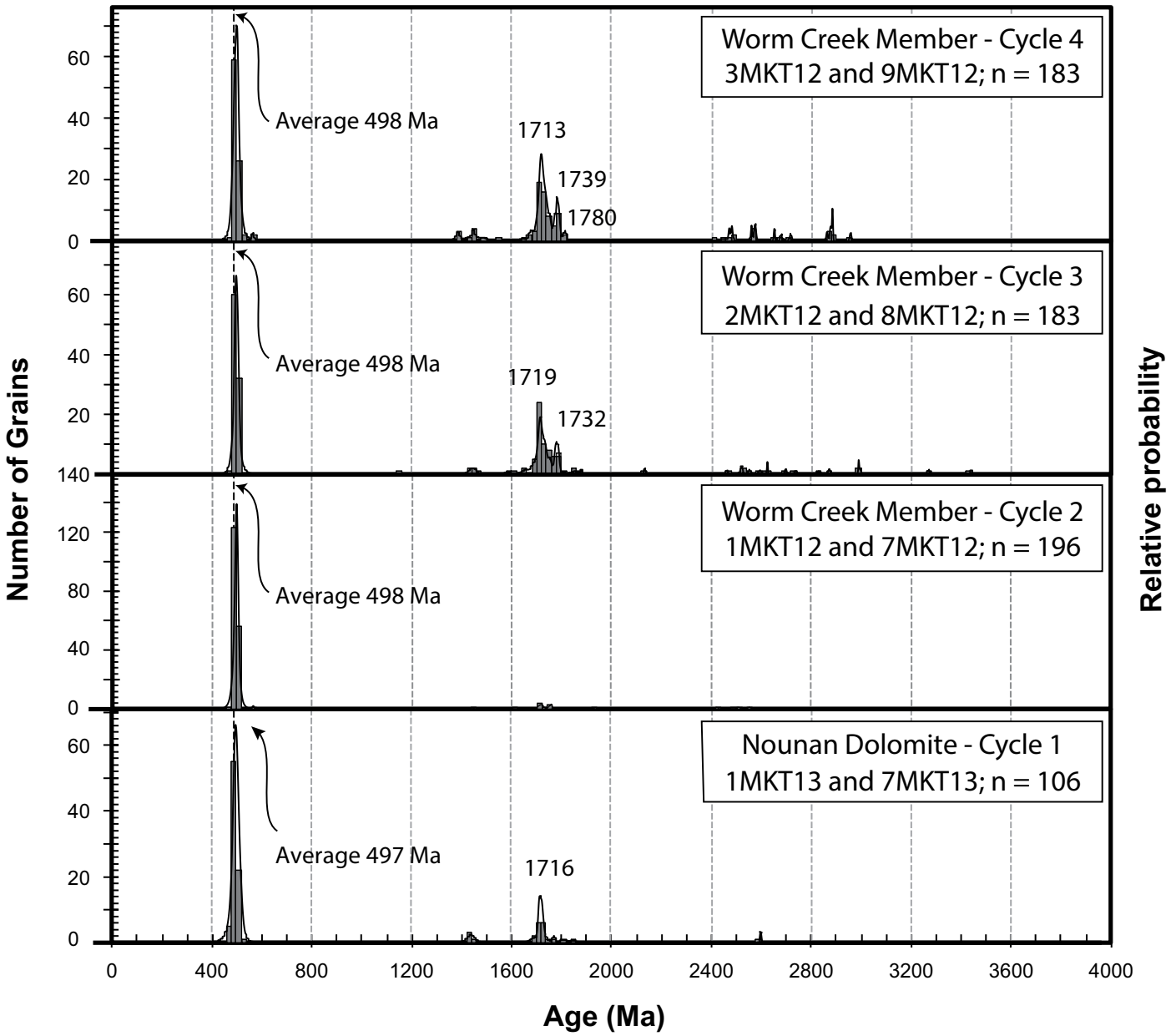

Figure 6. Histogram and probability density curves of detrital zircon ages from the four siliciclastic cycles of the Worm Creek sandstone, stacked stratigraphically. Weighted average of major peaks was calculated in Isoplot (Ludwig, 2003). Histogram bin width is 20 m.y. Data are in Data Repository Table DR1.

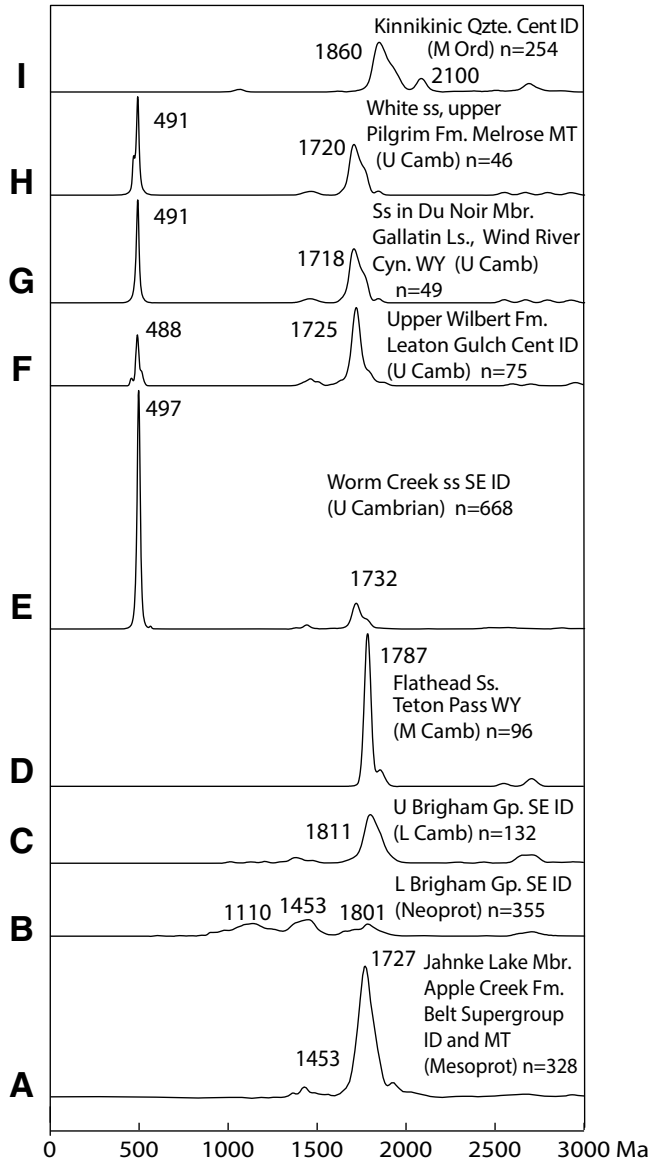

Figure 7. Comparative normalized U-Pb detrital zircon relative probability age plots from Mesoproterozoic to Ordovician (Ord) sandstones of Idaho, Montana, and Wyoming. Ages (Ma) of prominent peaks are shown. Number of grains and samples varies, but signatures are distinct. The sharp, near-unimodal peak ca. 497 Ma is present in the Worm Creek (plot E) and correlative Upper Cambrian sandstones (plots F, G, and H). I—Middle Ordovician Kinnikinic Quartzite, central Idaho (samples 5TA09, 9TD10, and 09LR01; from Beranek et al., 2016). H—Upper Cambrian sandstone within upper Pilgrim Limestone, Melrose, Montana (11PL03). G—sand in Upper Cambrian Du Noir Member of Gallatin Limestone, Wind River Canyon, Wyoming (12PL03). F—Upper Cambrian Wilbert Formation (uppermost formation of Leaton Gulch), south of Challis, Idaho (Carr and Link, 1999; Hargraves et al., 2007; sample 151PL02). E—Upper Cambrian Worm Creek Quartzite Member, St. Charles Formation, and upper Nounan Dolomite, southeast Idaho and northern Utah (Todt, 2014; 01MKT12, 02MKT12, 03MKT12, 07MKT12, 08MKT12, 09MKT12, 01MKT13, and 07MKT13). D—Middle Cambrian Flathead Sandstone, Teton Pass, Wyoming (1PL13). C—Lower Cambrian Upper Brigham Group, Gibson Jack Formation and Windy Pass Argillite (samples 9JK08, and 11JK08; from Yonkee et al., 2014). B—Neoproterozoic (Cryogenian) lower Brigham Group, Portneuf Range, Idaho and Utah; Caddy Canyon, Mutual, Browns Hole, and lower Camelback Mountain formations (from Yonkee et al., 2014) (Z083, Z084, Z085 1JK08,). A—Mesoproterozoic Jahnke Lake member of Apple Creek Formation and Lawson Creek Formation, Belt Supergroup, Beaverhead and Lemhi Ranges (samples 2PL11, 6PL11, JS1103, 3TS09, 9TS09, 12RL214, 8PL12, 7PL12, 5PL10, 49ES08, 46ES08; from Link et al., 2016, fig. 7 therein). Global positioning system locations of samples newly reported in this paper are listed in Table 1 and the Data Repository. Cent—Central; Cyn—Canyon; Gp—Group; ID—Idaho; L—Lower; Ls—Limestone; M—Middle; Mbr—Member; Mesoprot—Mesoproterozoic; MT—Montana; Neoprot—Neoproterozoic; Ss—Sandstone; U—Upper; Wy—Wyoming.

east of Melrose in southwest Montana, and Leaton Gulch near Challis, Idaho. Table 1 shows abbreviations for sample localities from Figures 1 and 3. Subsidence analysis (Fig. 8) was performed using BasinMod software (Platte River Associates, Inc.; www.platte.com/software/basinmod-2012.html).

We also analyzed magmatic zircons from four plutonic samples of the Deep Creek and Beaverhead granitoids, from the Beaverhead plutonic belt (Fig. 9). Lund et al. (2010) reported SHRIMP (sensitive high-resolution ion microprobe) U-Pb ages on these plutons. The reanalysis affords direct comparison of the ages and Lu-Hf isotope values of magmatic and detrital zircons using the same instrument and technique.

U-Pb zircon analyses from plutonic and detrital grains were acquired using laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) at the Arizona LaserChron Center following procedures given by Gehrels et al. (2006). Plots and age calculations were carried out using Isoplot (Ludwig, 2003). For igneous samples, cathodoluminescence images were used to check for inherited cores within the zircon crystals.

Ages with >10% discordance or >5% precision error were rejected and are not included in the results presented here. Weighted mean averages of grain ages from each pluton were calculated using Isoplot (Ludwig, 2003; U-Pb age uncertainties henceforth include internal and external errors at the 2σ level). Probability density plots with superposed 20 Ma bin width histograms were generated for the detrital samples using Isoplot to determine age peaks of each detrital sample (Figs. 6 and 7; Ludwig, 2003). We used a laser spot size of 30 µm. For grains younger than 1.0 Ga, we used $^{206}Pb/^{238}U$ ages, whereas we used $^{206}Pb/^{207}Pb$ ages for grains older than 1.0 Ga. The Kolmogorov-Smirnoff (K-S) test was used to determine if there are statistical differences between two samples' age distributions (DeGraaff-Surpless et al., 2003; Guynn and Gehrels, 2010).

LA-MC-ICP-MS was also used on selected 510–490 Ma zircon grains to measure the ratios of isotopes of Hf, using methods detailed in Cecil et al. (2011) and Gehrels and Pecha (2014). We conducted Hf analyses over the same pit as the U-Pb age spot. For large grains, we used a 50 µm spot for Hf analysis, whereas for smaller grains, we used a 40 µm spot size. Hf results are shown in Figure 10, where initial $^{176}Hf/^{177}Hf$ ratios are expressed in εHf(t) notation, which represents the Hf isotopic composition relative to the chondritic uniform reservoir at the time of zircon crystallization (Bouvier et al., 2008). Initial εHf(t) values that are <5 units below the depleted mantle are considered juvenile in composition, while values >12 units below the depleted mantle are evolved in composition; initial εHf values between 5 and 12 units below the depleted mantle values are classified as intermediate (Bahlburg et al., 2011). For this study, detrital zircon grains were chosen for Hf analysis based on their measured U-Pb ages between 510 and 490 Ma.

Plutonic grains were chosen based on their low U-Pb uncertainty and lack of inherited cores seen in cathodoluminescence images (see Fig. 4). Initial εHf results for each zircon grain analyzed are shown in Figure

TABLE 1. LOCATIONS AND DESIGNATIONS FOR SAMPLES ANALYZED IN THIS PAPER

Sample	Unit	Cycle	Zone	Easting	Northing	Elev. M	Fig. 1 or 3 location
Worm Creek Mbr. St. Charles Fm. and upper Nounan Dolomite, southeast Idaho							
01MKT12	Worm Creek - lower	2	12	376234	4731387	1916	MC-A
02MKT12	Worm Creek - middle	3	12	376385	4731422	1934	MC-A
03MKT12	Worm Creek - upper	4	12	376531	4731491	1922	MC-A
07MKT12	Worm Creek - lower	2	12	443855	4712685	1784	MP-B
08MKT12	Worm Creek - middle	3	12	443900	4712733	1803	MP-B
09MKT12	Worm Creek - upper	4	12	444025	4712786	1830	MP-B
07MKT13	Nounan Dolomite	1	12	393521	4681064	1938	WC-E
01MKT13	Nounan Dolomite	1	12	408301	4663365	1680	SC-D
Central Idaho, Western Wyoming, and Western Montana							
11PL03	upper Pilgrim Fm.		12	373250	5056777	1686	ML
12PL03	Du Noir Mbr Gallatin Ls		12	729039	4813897	1549	WR
151PL02	upper Wilbert Fm, Leaton Gulch, Skolithos		11	731909	4935574	2413	LG
1PL13	Flathead Sandstone		12	503752	4816270	2566	TP
Central Idaho Plutons							
05MKT12	Beaverhead Pluton		12	337841	4924094	2925	BHp
06MKT12	Beaverhead Pluton- adjacent to Ord. Kinnikinic Qzte. contact		12	338021	4923613	3043	BHp
01LKB12	Deep Creek Pluton		11	719077	5000741	1499	DCp
02LKB12	Deep Creek Pluton		11	718789	5002076	1516	DCp

Note: Locations are based on datum WGS84. See Data Repository.

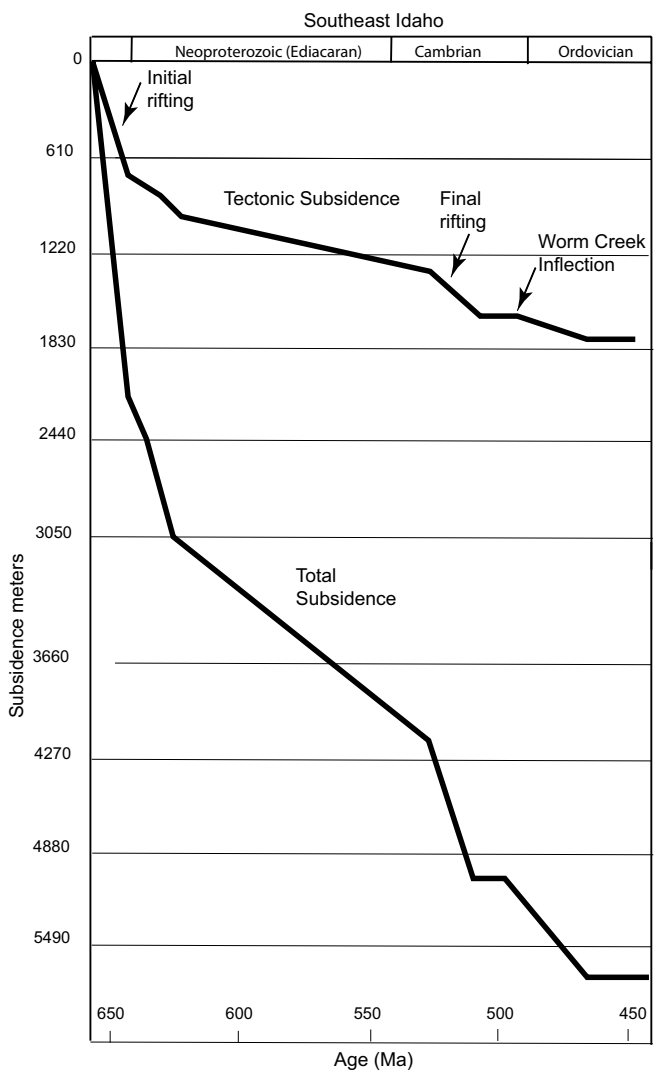

Figure 8. Tectonic subsidence and total subsidence curves for Neoproterozoic (Cryogenian) to Ordovician strata in the northern Bannock Range, southeast Idaho. Steep parts of curve show initial and final rifting. Inflection of both subsidence curves at 500 Ma corresponds to subsidence of the Worm Creek basin. Curve flattens into the Ordovician with the deposition of the Garden City Formation and Swan Peak Quartzite. Thickness and depositional environment data start from the Caddy Canyon Quartzite (Fig. 2) and are from Trimble and Carr (1976) and Link et al. (1987). Subsidence was calculated using BasinMod software developed by Platte River Associates, Inc. (www.platte.com/software/basinmod-2012.html). The software takes input for geologic age (top of the unit), thickness, lithology and general depositional environment. This allows calculation of water depth and compaction. Compaction is calculated using the Statoil fluid flow porosity reduction method: $\Phi = \phi_0 \times \exp(-C \times S_{eff})$: ϕ = calculated porosity; Φ_0 = initial porosity; C = Statoil compaction exponent; and S_{eff} = effective stress.

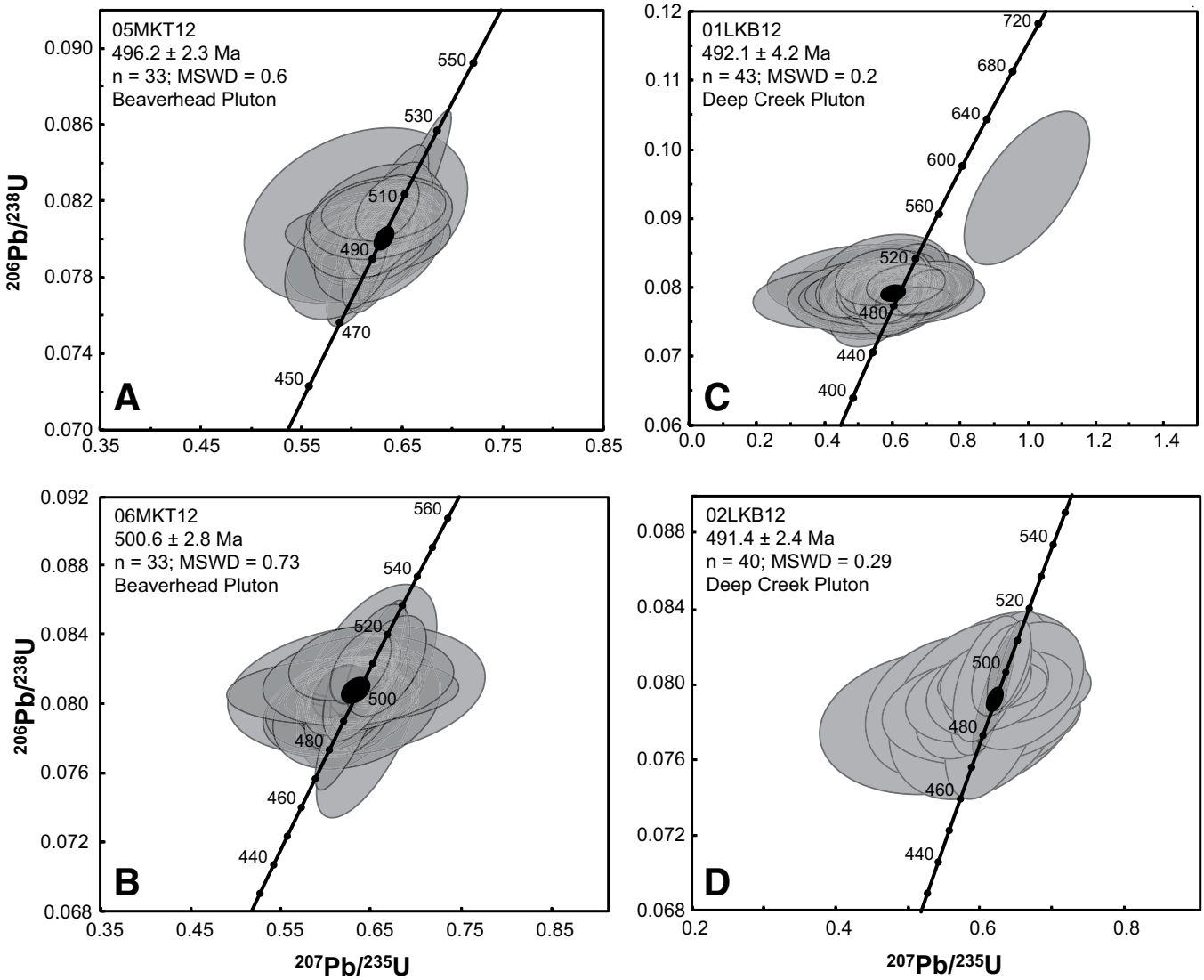

Figure 9. (A–D) Concordia plots showing laser ablation–multicollector–inductively coupled plasma–mass spectrometry U-Pb isotopic data for pluton samples. Values of individual grains are shown with 1σ error ellipses; no discordant grains were analyzed. Included for each sample are weighted mean ages with 2σ uncertainty, number of grains plotted, and mean square of weighted deviates (MSWD).

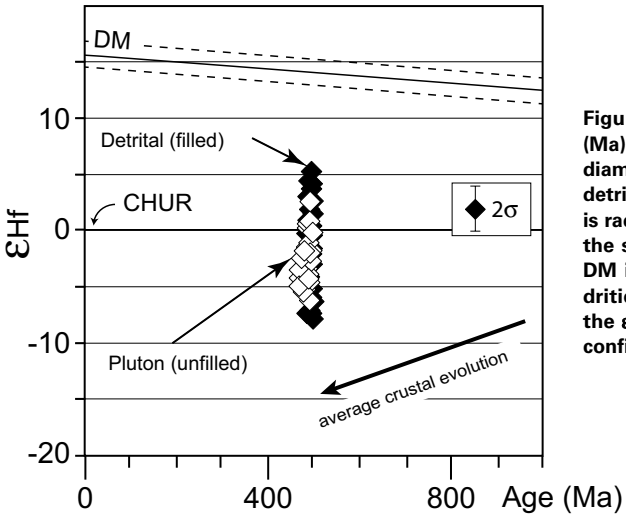

Figure 10. Zircon εHf values versus age (Ma) for the two sampled plutons (white diamonds) and the 510–490 Ma analyzed detrital grains (black diamonds). The ^{176}Hf is radiogenic, from decay of ^{176}Lu; ^{177}Hf is the stable isotope. The εHf is ^{176}Hf/^{177}Hf. DM is depleted mantle; CHUR is chondritic uniform reservoir, and represents the εHf of the average Earth; 2σ is 95% confidence level of the analysis.

10. They were plotted with their corresponding U-Pb ages and 1σ εHf uncertainties. The average internal precision for εHf(t) data presented here is 2 epsilon units (2σ).

RESULTS

Late Cambrian Subsidence and Upper Cambrian Stratigraphy

Ediacaran to Ordovician tectonic and total subsidence curves (Fig. 8) for the northern Bannock Range were calculated using BasinMod software. The subsidence curves show a decrease and then increase in subsidence rate, immediately before and during deposition of the Worm Creek sandstone. We suggest that this change in subsidence rate is linked with emplacement, cooling, and exhumation of Beaverhead plutons and punctuated subsidence of the Worm Creek sedimentary basin. The subsidence curves also show earlier periods of rapid subsidence corresponding with initial and final rifting of the passive margin (Yonkee et al., 2014).

Zircon U-Pb Ages and Hf Isotopes

Worm Creek Sandstone: Detrital Zircon Analyses

The extraordinary aspect of the U-Pb ages of detrital zircon grains in all of the sandstones is the large near-unimodal population of ages of 498–497 Ma (Fig. 6) that overlaps with the *Crepicephalus* trilobite zone (498.5–497 Ma). The presence of this detrital zircon population was suspected from analysis of zircons in modern streams draining areas where the Worm Creek sandstone crops out (Link et al., 2005). All 4 siliciclastic cycles have average ages of 498–497 Ma. These 498–497 Ma zircon grains are typically clear and subrounded, with simple oscillatory zoning (Figs. 4G, 4H). Subordinate Paleoproterozoic (mainly 1750–1700 Ma) and Archean zircon grains are darker colored, light pink to violet, rounded, and complexly zoned. These detrital grains are interpreted as recycled from uppermost Belt Supergroup (Fig. 7A; Burmester et al., 2016), the country rock for the Beaverhead granitoids (Skipp, 1984; Link et al., 2007, 2016).

The dominant age peak (54% of zircon grains) for the first cycle of siliciclastic sedimentation is 497 Ma, with a smaller age group (15%) of 1716 Ma grains (Fig. 6). The defining unimodal age peak (85%) for the second cycle is 498 Ma. Proterozoic grains are sparse. The third cycle has an age peak of similar magnitude to the first cycle peak at 498 Ma (44%); subordinate age groups have average peaks at 1719 and 1732 Ma (32%) and 3.0–2.5 Ga (8%). The fourth siliciclastic cycle has a signature similar to that of the third cycle. There is a slightly stronger Paleoproterozoic signature at 1740–1710 Ma and a dominant age peak at 498 Ma (41%).

The K-S two-sample test was used to assess the similarity of the 510–480 Ma grains from the 4 siliciclastic cycles (data are in Table DR2 in the GSA Data Repository Item[2]; see Todt, 2014). P values are consistently high (0.753–1.000), allowing that zircons in all of the four Upper Cambrian siliciclastic cycles could be derived from the same source population (e.g., Berry et al., 2001; DeGraaff-Surpless et al., 2003).

We utilized Hf isotopic analysis of detrital zircon grains with U-Pb ages of 510–490 Ma to compare Worm Creek sandstones with coeval plutons of the Beaverhead plutonic suite. The detrital zircons have a spread of intermediate to evolved initial εHf values from −8.0 ± 1.9 to 5.4 ± 1.2 (Fig. 9).

[2]GSA Data Repository Item 2017339, four tables: DR1—Locations and description of samples, DR2—U-Pb zircon data, DR3—Lu-Hf isotope data on dated zircon grains, DR4—Results of Kolmogorov-Smirnov tests on detrital zircon samples, is available at http://www.geosociety.org/datarepository/2017, or on request from editing@geosociety.org.

Other Cambrian Sandstones

Zircons from the Middle Cambrian Flathead Sandstone at Teton Pass, Wyoming, have a major age peak at 1787 Ma (Fig. 7D). In contrast, white sandstone beds within the Upper Cambrian Pilgrim Limestone, Melrose, Montana (Fig. 7H), and sand in the Upper Cambrian Du Noir Member of the Gallatin Limestone, Wind River Canyon, Wyoming (Fig. 7G), share a major 491 Ma age peak. Sandstone from the uppermost part of the Upper Cambrian Wilbert Formation at Leaton Gulch, south of Challis, Idaho (Carr and Link, 1999; Hargraves et al., 2007), has a 488 Ma zircon age peak (Fig. 7F).

Lu-Hf Isotopes from Plutonic Zircons

We analyzed U-Pb and Lu-Hf in zircon from four plutonic samples from the Deep Creek (two samples) and Beaverhead plutons (two samples) of the Beaverhead plutonic suite north of the Snake River Plain (Figs. 9 and 10). The Deep Creek pluton yielded U-Pb LA-ICP-MS ages of 492 ± 4 Ma and 491 ± 2 Ma, and the Beaverhead pluton produced ages of 496 ± 2 Ma and 500 ± 3 Ma (Fig. 9). These ages are close to, but not precisely the same as, the SHRIMP ages reported by Lund et al. (2010) of 497 ± 6 Ma (Deep Creek) and 488 ± 5 Ma (Beaverhead). Ages from the Deep Creek pluton overlap within error, while the SHRIMP age for the Beaverhead pluton is slightly younger than our ages. The 500–490 Ma zircons from the plutons have an intermediate to evolved initial εHf range of −5.4 ± 1.1 to −2.2 ± 0.9 for the Deep Creek pluton and −6.3 ± 1.1 to 2.7 ± 1.4 for the Beaverhead pluton (Fig. 10).

DISCUSSION

Provenance Relationships

Given the excellent match in U-Pb age and initial εHf values from both magmatic and detrital zircons, we conclude that the Beaverhead plutonic suite was the primary source for the flood of 500–490 Ma zircon grains and detrital potassium feldspar in the Upper Cambrian Worm Creek sandstones of the southeast Idaho thrust belt (Figs. 6 and 7E). By transport to more distal locations within the continental shelf, young 500–490 Ma zircon grains were also deposited in the Upper Cambrian Du Noir Limestone on the Wyoming craton and the Pilgrim Formation on the southwest Montana cratonal shelf (Figs. 7G, 7H). To the west, in the Cordilleran thrust belt, this young grain population is also present in the upper Wilbert Formation at Leaton Gulch in the northern Lost River Range (Fig. 7F). Within the Antler assemblage at Pete's Summit in the Toquima Range of central Nevada (Fig. 11), the Ordovician lower Vinini Formation also contains this zircon population; 29 of 189 grains are between 503 and 480 Ma (Linde et al., 2016).

Transcontinental Arch

Detrital zircon evidence from Neoproterozoic and Cambrian sandstones in Idaho as well as in the Roberts Mountains allochthon of the Devonian Antler orogenic belt in central Nevada suggests that in Early Cambrian time, the Transcontinental Arch rose in the central United States (see Fig. 11). This cut off the supply of Mesoproterozoic, Grenville-age (1250–950 Ma) zircons to the western continental margin (Linde et al., 2014; Yonkee et al., 2014).

Rapid Pluton Exhumation or Coeval Volcanism

The Worm Creek sandstones contain 500–490 Ma detrital zircons with ages nearly the same as biostratigraphic ages of the host strata, and

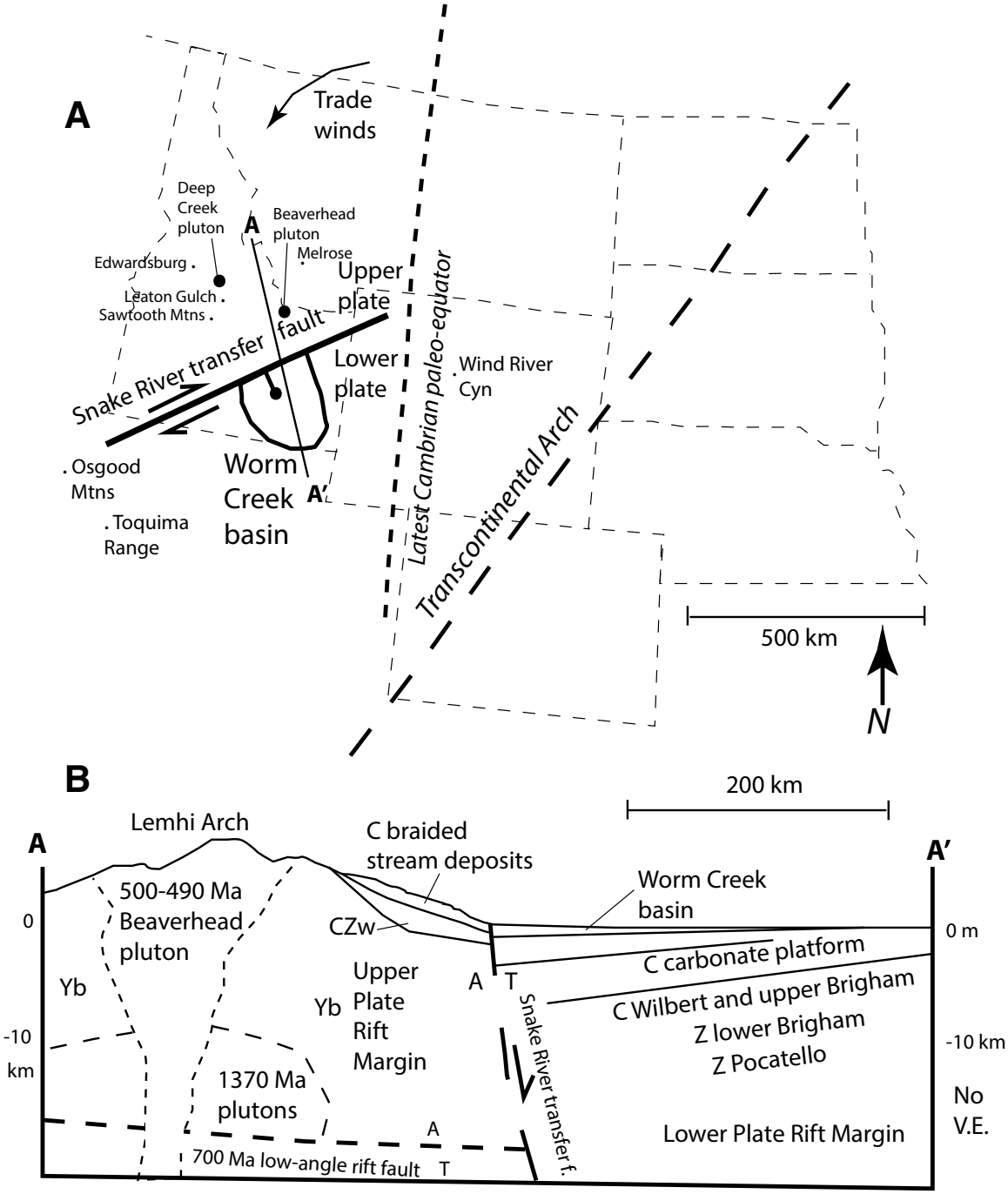

Figure 11. (A) Map relations and location of cross section in B. Cyn—canyon. (B) Generalized cross section showing schematic interpretation for latest Cambrian time, with the Beaverhead pluton to the north of the Snake River Plain supplying arkosic sediment to the Worm Creek basin on the south side of the Snake River transfer fault. Key locations mentioned in text are also shown. Location of Worm Creek basin southern onlap is based on Coulter (1956). Hypothetical braided stream system that supplied plutonic debris to marine shoreline is shown. Yb—Mesoproterozoic Belt Supergroup; CZw—Neoproterozoic–Cambrian Wilbert Formation; C—Cambrian; Z—Neoproterozoic; Y—Mesoproterozoic; A—away; T—toward. Trade winds (from Amato and Mack, 2012) are consistent with generally east-west shoreline inferred from paleocurrents in northern Utah. V.E.—vertical exaggeration.

geochronologic ages of magmatic zircon from the Deep Creek and Beaverhead plutons. This suggests rapid emplacement and erosion of the plutons and near contemporaneous deposition of the Worm Creek sandstones. The flood of zircons reached at least as far east as central Wyoming on the Laurentian craton. Perthitic textures in large grains (Fig. 4C) suggest a plutonic source. X-ray diffraction identification of microcline suggests that the immediate source for the feldspar was plutonic rather than volcanic (Deer et al., 1992; Todt, 2014). This is consistent with the hypabyssal nature of the Beaverhead plutonic suite (Evans and Zartman, 1988; Lund et al., 2010).

The subrounded shapes of the zircon grains are surprising given the proximity (a few hundred kilometers) of the depositional site to the plutonic source. The subrounded shape is interpreted to indicate extensive reworking in tidal sand bodies as opposed to less reworking in the fluvial systems studied by Link et al. (2005) and Zoleikhaei et al. (2016).

Regional Implications

We are now able to reconstruct a predictable succession of Neoproterozoic to Paleozoic detrital zircon age populations in southern and central Idaho, shown in Figure 7. Sources of zircon grains of a given age were reviewed in Link et al. (2005), Balgord et al. (2013), and Yonkee et al. (2014). South of the Snake River Plain, the Ediacaran (635–540 Ma) lower Brigham Group (Fig. 7B) has a diverse provenance that includes 1250–950 Ma grains from the Grenville orogen, Mesoproterozoic grains (1.47–1.40 Ga), and Paleoproterozoic grains (1.8–1.6 Ga), likely derived or recycled from the Yavapai-Mazatzal provinces. Archean grains are also present. This Laurentian integrated provenance is common in Paleozoic passive margin sandstones of western North America (Gehrels and Pecha, 2014) and is labeled type II in Cambrian sandstones of the northern Canadian Cordillera (Hadlari et al., 2012).

At the top of the Brigham Group (Fig. 7C, Lower Cambrian), and in the Middle Cambrian Flathead Sandstone on the Wyoming craton (Fig. 7D), the Grenville age peak disappears and the bulk of the zircons are 1.8–1.75 Ga (Figs. 7B, 7C). Strata mapped as Flathead Sandstone in southwest Montana are notable because they regionally overlie Archean basement but contain mainly 1790 Ma Paleoproterozoic grains (Mahoney et al., 2015). The upper Brigham Group lacks Grenville-age grains. We infer that these grains were cut off by rise of the Transcontinental Arch in Early Cambrian time (Yonkee et al., 2014; Linde et al., 2014).

The Worm Creek sandstones have very a different and much more specific detrital zircon distribution. The near unimodal, 500–490 Ma ages of detrital zircons in the Worm Creek sandstones (Fig. 7D) are interpreted to represent a local flood of grains from the Beaverhead plutons. This signals proximal siliciclastic sediment delivery to the passive margin. Smaller amounts of zircon of this age are found in more distal strata, from the Wilbert Formation at Leaton Gulch (Fig. 7F) in central Idaho, eastward to the Pilgrim Formation near Melrose, Montana (Fig. 7H), and sandstone in the Du Noir Member, Gallatin Limestone, in the Wind River Canyon on the Wyoming craton (Fig. 7G). Small groups of Paleoproterozoic (mainly 1750–1700 Ma) grains in the Worm Creek sandstones are interpreted to be recycled from the uppermost Belt Supergroup (Swauger Formation and overlying Jahnke Lake member of the Apple Creek Formation; Fig. 7A) (Link et al., 2007, 2016), which are country rock to the plutons. In the second siliciclastic cycle of the Worm Creek sandstone (Fig. 6B), Paleoproterozoic grains are sparse, their signature nearly flooded out by 500–490 Ma grains derived from the Beaverhead plutons.

Stratigraphically above the Worm Creek sandstone, the Middle Ordovician Kinnikinic Quartzite (and the correlative Swan Peak Quartzite south of the Snake River Plain; Wulf, 2011) have a mainly Paleoproterozoic provenance, with almost all grains older than 1.8 Ga, a peak at 1860 Ma, and no younger grains (Fig. 7I; Baar, 2009; Beranek et al., 2016). The provenance is interpreted to have been from the Peace River Arch in Alberta. This signature is prominent in Middle Ordovician sandstones of the Canadian Cordillera and Nevada (Gehrels and Pecha, 2014) as well as in central Idaho (Beranek et al., 2016). In the Sawtooth Mountains (Fig. 11) it is group B of Ma et al. (2016). In Cambrian strata of the northern Canadian Cordillera, it is provenance type I of Hadlari et al. (2012).

Hf Isotope Discussion: Mesoproterozoic Parent for Cambrian Plutons

Initial εHf isotope compositions of zircon help differentiate between a lithospheric (evolved) versus asthenospheric (juvenile) source, or the extent of crustal contamination during magmatism (Kinny and Maas, 2003; Goodge and Vervoort, 2006; Cecil et al., 2011; Gehrels and Pecha, 2014). The 500–490 Ma Deep Creek and Beaverhead plutons have intermediate to evolved initial εHf of −6.3 ± 1.1 to 2.7 ± 1.4. This range overlaps that of Neoproterozoic plutons in the Pioneer Mountains, with initial εHf of −2.4–3.4 in 675 Ma detrital grains (Link et al., 2017).

These intermediate initial εHf values suggest limited reintegration of evolved Archean lithosphere. They are consistent with the Mesoproterozoic lithospheric source hypothesized to occur beneath the southwestern portion of the Belt basin (Doughty and Chamberlain, 1996; Elk City domain of Gaschnig et al., 2013; Fig. 1B). The Cambrian plutons occur in crust previously modified by a northwest-trending belt of Mesoproterozoic plutons and concomitant mafic sills (ca. 1370 Ma) intruded into the lower crust during the final stages of Belt basin subsidence (Fig. 1B; Doughty and Chamberlain, 1996). We suggest that a fundamental cause for the Lemhi arch, and its lack of overlying Neoproterozoic strata, as well as the Big Creek–Beaverhead belt of Neoproterozoic and Cambrian plutons, is this post-Belt Mesoproterozoic underpinning (Fig. 1 inset).

Tectonic Model

The flood of feldspathic sand in the Worm Creek sandstones was coupled with an increase in tectonic subsidence and accommodation (Fig. 8) within the thermally subsiding Ediacaran to Ordovician continental terrace in southeast Idaho. We interpret the Snake River dextral transfer fault (Fig. 1) of Lund et al. (2010) to have had dextral normal movement (Fig. 11), and to have accommodated the northward transition from the passive margin in southeast Idaho to the Lemhi arch. The amount of dextral strike slip on this fault must have been less than 100 km, since strata correlative with the passive margin at Pocatello are found to the northwest at Stibnite and Edwardsburg (Figs. 1, 11) (Lewis et al., 2014; Stewart et al., 2016). Sediment was transported southward from uplifted Beaverhead and Deep Creek plutons, across the Snake River transfer fault from the Lemhi arch and its upper Belt Supergroup country rock. The latest Cambrian Worm Creek basin formed on the hanging wall of the fault separating upper and lower plate margins (Fig. 11).

By east-west transport across the Laurentian continental shelf, 500 Ma Beaverhead magmatic zircons reached the Du Noir Limestone in Wind River Canyon in Wyoming (Fig. 7G), the Pilgrim Formation on Montana shelf to the north (Fig. 7H), and the thrust belt in central Idaho (Fig. 7F).

The presence of 500–490 Ma magmatic zircon grains in the Antler allochthon in central Nevada (Linde et al., 2016) demonstrates linkages from the Laurentian craton to the western thrust belt. This raises doubt about models of the exotic Rubia ribbon continent, the eastern margin of which is predicted to be within the Idaho thrust belt (Johnston, 2008; Hildebrand, 2009).

CONCLUSIONS

Similar U-Pb zircon ages, coupled with the overlap in εHf values between the Upper Cambrian Worm Creek sandstone and the Cambrian–Ordovician plutons of the alkalic Beaverhead plutonic suite, suggest that the plutons were the source for the sandstones. This requires rapid exhumation and erosion of the plutons into the actively subsiding Worm Creek basin. These 500–490 Ma zircons were transported across the continental shelf as far east as the Wind River Canyon on the Wyoming craton, and as far west as Leaton Gulch in the central Idaho thrust belt.

These results support the model of long-lived Rodinian rifting along the western margin of Laurentia; they also suggest the existence of the dextral-normal Snake River transfer fault, a major transverse structure separated a region of ongoing magmatism and exhumation from one of subsidence and passive margin sedimentation. The spatial overlap between the ca. 1.4 Ga Mesoproterozoic Belt basin and Lemhi subbasin, ca. 1.37 Ga mafic intrusions, and the partially exhumed Lemhi arch suggest that the shape of the Laurentian rifted margin was controlled by the preexisting lithospheric architecture, perhaps due to strengthening of the lower crust during Mesoproterozoic mafic magmatism.

Rather than being tectonically quiet in central Idaho, the Cambrian was a time of magmatism and uplift. The Beaverhead and Deep Creek alkalic intrusions were emplaced, uplifted, and eroded. The Worm Creek basin south of the Snake River Plain subsided and was filled close to sea level with feldspathic sand derived from those plutons.

The coincidence of the uplift of the Lemhi arch and erosion of the Beaverhead plutons with the Steptoean positive isotope carbon excursion begs consideration of causality. The fundamental issue is whether the volume of uplifted Lemhi arch (estimated as 2×10^4 km^3 from area shown in Fig. 1B, and 0.5 km uplift) could have caused one of the Steptoean eustatic drops documented by Haq and Schutter (2008). In Link and Janecke (2009), it was suggested that mantle drip may have been a cause of Lemhi arch exhumation. At this point we only note that latest Cambrian uplift in central Idaho was coeval with both Laurentian and worldwide sea-level drop.

ACKNOWLEDGMENTS

Steve Oriel and Pete Palmer pointed out the anomalous Worm Creek sandstone more than forty years ago. This work was supported by grants to Todt from ExxonMobil, the Idaho State University (ISU) Research Committee, the Geological Society of America, the Geslin Fund of the ISU Department of Geosciences, and the Tobacco Root Geological Society. Staff members of the Arizona LaserChron Center (supported by National Science Foundation grant EAR-1338583) were of constant help. Mike McCurry provided valuable input on X-ray diffraction, and Diana Boyack helped a great deal with figures. Aaron Morse negotiated the BasinMod software, provided for educational use by Platte River Associates, Inc. This paper was reviewed by Gwen Linde and four anonymous reviewers.

REFERENCES CITED

Amato, J.M., and Mack, G.H., 2012, Detrital zircon geochronometry from the Cambrian–Ordovician Bliss Sandstone, New Mexico: Evidence for contrasting Grenville-age and Cambrian sources on opposite sides of the transcontinental Arch: Geological Society of America Bulletin, v. 124, p. 1826–1840, doi:10.1130/B30657.1.

Armstrong, F.C., and Oriel, S.S., 1965, Tectonic development of the Idaho-Wyoming thrust belt: American Association of Petroleum Geologists Bulletin, v. 49, p. 1847–1866.

Armstrong, F.C., and Oriel, S.S., 1982, Tectonic development of the Idaho-Wyoming thrust belt, *in* Peterson, J. A., ed., Paleotectonics and sedimentation: American Association of Petroleum Geologists Memoir 41, p. 243–279, doi:10.1306/M41456C12.

Armstrong, R.L., 1975, Precambrian (1500 m.y. old) rocks of central Idaho–The Salmon River arch and its role in Cordilleran sedimentation and tectonics: American Journal of Science, v. 275-A, p. 437–467.

Baar, E.E., 2009, Determining the regional-scale detrital zircon provenance of the Middle-Late Ordovician Kinnikinic (Eureka) Quartzite, east-central Idaho, U.S. [M.S. thesis]: Pullman, Washington State University, 134 p.

Bahlburg, H., Vervoort, J.D., DuFrane, S.A., Carlotto, V., Reimann, C., and Cárdenas, J., 2011, The U-Pb and Hf isotope evidence of detrital zircons of the Ordovician Ollantaytambo Formation, southern Peru, and the Ordovician provenance and paleogeography of southern Peru and northern Bolivia: Journal of South American Earth Sciences, v. 32, p. 196–209, doi:10.1016/j.jsames.2011.07.002.

Balgord, E.A., Yonkee, W.A., Link, P.K., and Fanning, C.M., 2013, Stratigraphic, geochronologic, and geochemical record of the Cryogenian Perry Canyon Formation, northern Utah: Implications for Rodinia rifting and snowball Earth glaciation: Geological Society of America Bulletin, v. 125, p. 1442–1467, doi:10.1130/B30860.1.

Beranek, L.P., Link, P.K., and Fanning, C.M., 2016, Detrital zircon record of mid-Paleozoic convergent margin activity in the northern U.S. Rocky Mountains: Implications for the Antler orogeny and early evolution of the North American Cordillera: Lithosphere, v. 8, p. 533–550, doi:10.1130/L557.1.

Berry, R.F., Jenner, G.A., Meffre, S., and Tubrett, M.N., 2001, A North American provenance for Neoproterozoic to Cambrian sandstones in Tasmania?: Earth and Planetary Science Letters, v. 192, p. 207–222, doi:10.1016/S0012-821X(01)00436-8.

Bond, G.C., and Kominz, M.A., 1984, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains—Implications for subsidence mechanisms, age of break-up and crustal thinning: Geological Society of America Bulletin, v. 95, p. 155–173, doi:10.1130/0016-7606(1984)95<155:COTSCF>2.0.CO;2.

Bond, G.C., Christie-Blick, N., Kominz, M.A., and Devlin, W.J., 1985, An early Cambrian rift to post-rift transition in the Cordillera of western North America: Nature, v. 315, p. 742–746, doi:10.1038/315742a0.

Bouvier, A., Vervoort, J.D., and Patchett, P.J., 2008, The Lu-Hf and Sm-Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets: Earth and Planetary Science Letters, v. 273, p. 48–57, doi:10.1016/j.epsl.2008.06.010.

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., eds., Belt Basin: Window to Mesoproterozoic Earth: Geological Society of America Special Paper 522, p. 121–137, doi: 10.1130/2016.2522(05)

Bush, J., Thomas, R.C., and Pope, M.C., 2012, Sauk megasequence deposition in northeastern Washington, northern Idaho, and western Montana, *in* Derby, J.R., et al., eds., The great American carbonate bank: The geology and economic resources of the Cambrian–Ordovician megasequence of Laurentia: American Association of Petroleum Geologists Memoir 98, p. 751–768.

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: Pocatello, Idaho Museum of Natural History, p. 21–29.

Cecil, M.R., Gehrels, G.E., Ducea, M.N., and Patchett, P.J., 2011, U-Pb-Hf characterization of the central Coast Mountains batholith: Implications for petrogenesis and crustal architecture: Lithosphere, v. 3, p. 247–260, doi:10.1130/L134.1.

Christie-Blick, N., and Levy, M., 1989, Stratigraphic and tectonic framework of upper Proterozoic and Cambrian rocks in the western United States, *in* Christie-Blick, N., and Levy, M., eds., Late Proterozoic and Cambrian tectonics, sedimentation, and record of metazoan radiation in the western United States: American Geophysical Union Field Trip Guidebook T331, p. 7–21, doi:10.1029/FT331p0007.

Coulter, H.W., 1956, Geology of the southeast portion of the Preston Quadrangle, Idaho: Moscow, University of Idaho Pamphlet 107, 55 p.

Deer, W.A., Howie, R.A., and Zussman, J., 1992, An introduction to the rock-forming minerals (second edition): Hong Kong, Longman Scientific and Technical, 696 p.

DeGraaff-Surpless, K., Mahoney, J.B., Wooden, J.L., and McWilliams, M.O., 2003, Lithofacies control in detrital zircon provenance studies: Insights from the Cretaceous Methow Basin: Geological Society of America Bulletin, v. 115, p. 899–915, doi:10.1130/B25267.1.

Dickinson, W.R., 2004, Evolution of the North American Cordillera: Annual Review of Earth and Planetary Sciences, v. 32, p. 13–45, doi:10.1146/annurev.earth.32.101802.120257.

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, p. 1037–1052, doi:10.1139/e96-079.

Durk, K.M., Link, P.K., and Fanning, C.M., 2007, Neoproterozoic 695 Ma orthogneiss, Wildhorse Creek, Pioneer Mountains, south-central Idaho: New tie point in reconstruction of Rodinian rifting: Geological Society of America Abstracts with Programs, v. 36, no. 6, p. 613.

Evans, K.V., and Zartman, R.E., 1988, Early Paleozoic alkalic plutonism in east-central Idaho: Geological Society of America Bulletin, v. 100, p. 1981–1987, doi:10.1130/0016-7606(1988)100<1981:EPAPIE>2.3.CO;2.

Foster, D.A., Mueller, P.A., Heatherington, A., Gifford, J.N., and Kalakay, T.J., 2012, Lu-Hf systematics of magmatic zircons reveal a Proterozoic crustal boundary under the Cretaceous Pioneer batholith, Montana: Lithos, v. 142–143, p. 216–225, doi:10.1016/j.lithos.2012.03.005.

Gardiner, L.L., 1974, Environmental analysis of the Upper Cambrian Nounan Formation, Bear River Range and Wellsville Mountain, north-central Utah [M.S. thesis]: Logan, Utah State University, 135 p.

Gaschnig, R.M., Vervoort, J.D., Lewis, R.S., and Tikoff, B., 2013, Probing for Proterozoic and Archean crust in the northern U.S. Cordillera with inherited zircon from the Idaho batholith: Geological Society of America Bulletin, v. 125, p. 73–88, doi:10.1130/B30583.1.

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.

Gehrels, G., Valencia, V., and Pullen, A., 2006, Detrital zircon geochronology by laser-ablation multicollector ICPMS at the Arizona LaserChron Center, *in* Olszewski, T., ed., Geochronology: Emerging opportunities: Paleontological Society Short Course: Paleontological Society Papers, v. 12, 67 p.

Goodge, J.W., and Vervoort, J.D., 2006, Origin of Mesoproterozoic A-type granites in Laurentia; Hf isotope evidence: Earth and Planetary Science Letters, v. 243, p. 711–731, doi:10.1016/j.epsl.2006.01.040.

Gradstein, F.M., Ogg, J.G., Schmitz, M., and Ogg, G., 2012, The geologic time scale 2012: Boston, Elsevier, 1176 p., doi:10.1016/B978-0-444-59425-9.00004-4.

Guynn, J., and Gehrels, G., 2010, Comparison of detrital zircon age distributions using the K-S test: Tucson, University of Arizona, Arizona LaserChron Center, 16 p.

Hadlari, T., Davis, W.J., Dewing, K., Heaman, L.M., Lemieux, Y., Ootes, L., Pratt, B.R., and Pyle, L.J., 2012, Two detrital zircon signatures for the Cambrian passive margin of northern Laurentia highlighted by new U-Pb results from northern Canada: Geological Society of America Bulletin, v. 124, p. 1155–1168, doi:10.1130/B30530.1.

Hansen, C.M., 2015, An investigation into the Poison Creek thrust: A Sevier thrust with Proterozoic Implications. [M.S. thesis]: Pocatello, Idaho State University, 79 p.

Hansen, C.M., and Pearson, D.M., 2016, Geologic map of the Poison Creek thrust fault and vicinity, Lemhi County, Idaho: Idaho Geological Survey Technical Report T-16-1, scale: 1:24,000.

Haq, B.U., and Schutter, S.R., 2008, A chronology of Paleozoic sea-level changes: Science, v. 322, p. 64–68, doi:10.1126/science.1161648.

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, *in* Link, P.K., and Lewis, R.S., eds., Proterozoic geology of western North America and Siberia: SEPM (Society for Sedimentary Geology) Special Publication 86, p. 167–174, doi:10.2110/pec.07.86.0167.

Haynie, A.V., Jr., 1957, The Worm Creek Quartzite Member of the St. Charles Formation, Utah-Idaho [M.S. thesis]: Logan, Utah State University, 39 p.

Hildebrand, R.S., 2009, Did westward subduction cause Cretaceous–Tertiary orogeny in the North American Cordillera?: Geological Society of America Special Paper 457, 71 p., doi: 10.1130/2009.2457.

Hintze, L.F., and Kowallis, B.J., 2009, Geologic history of Utah; a field guide to Utah's rocks: Brigham Young University Department of Geology Special Publication 9, 225 p.

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

Hobbs, S.W., Hays, W.H., and McIntyre, D.H., 1991, Geologic map of the Bayhorse area, central Custer County, Idaho: U.S. Geological Survey Miscellaneous Investigations Series Map I-1882, scale 1:62,500.

Hogan, J.P., and Gilbert, M.C., 1998, The southern Oklahoma aulacogen: A Cambrian analog for Mid-Proterozoic AMCG (anorthosite-mangerite-charnokite-granite) complexes?, *in* Hogan, J.P., and Gilbert, M.C., eds., Basement tectonics 12: Netherlands, Kluwer Academic Publishers, p. 39–78, doi:10.1007/978-94-011-5098-9_3.

Howell, B.F., Bridge, J., Deiss, C.F., Edwards, I., Lochman, C., Raasch, G.O., Reeser, C.E., Duncan, D.C., Mason, J.F., and Denson, N.M., 1944, Correlation of the Cambrian formations of North America: Geological Society of America Bulletin, v. 55, p. 993–1004, doi:10.1130/GSAB-55-993.

James, W.C., and Oaks, R.Q., Jr., 1977, Petrology of the Kinnikinic Quartzite (Middle Ordovician), east-central Idaho: Journal of Sedimentary Petrology, v. 47, p. 1491–1511.

Johnston, S.T., 2008, The Cordilleran ribbon continent of North America: Annual Review of Earth and Planetary Sciences, v. 36, p. 495–530, doi:10.1146/annurev.earth.36.031207.124331.

Keeley, J.A., Link, P.K., Fanning, C.M., and Schmitz, M.D., 2013, Pre- to syn-glacial rift-related volcanism in the Neoproterozoic (Cryogenian) Pocatello Formation, southeast Idaho: New SHRIMP and Ca-ID-TIMS constraints: Lithosphere, v. 5, p. 128–150, doi:10.1130/L226.1.

Kinny, P.D., and Maas, R., 2003, Lu-Hf and Sm-Nd isotope systems in zircon: Reviews in Mineralogy and Geochemistry, v. 53, p. 327–341, doi:10.2113/0530327.

Larsen, E.E., Patterson, P.E., Curtis, C., Drake, R., and Mutschler, F.E., 1985, Petrologic, paleomagnetic, and structural evidence of a Paleozoic rift system in Oklahoma, new Mexico, Colorado, and Utah: Geological Society of America Bulletin, v. 96, p. 1364–1372, doi: 10.1130/0016-7606(1985)96<1364:PPASEO.2.3.CO;2.

Lewis, R.S., Link, P.K., Stanford, L.R., and Long, S.P., 2012, Geologic map of Idaho: Idaho Geological Survey Map M-9, scale 1:750,000.

Lewis, R.S., Stewart, D.E., Schwartz, D.M., Stewart, E.D., Isakson, V.H., and Vervoort, J.D., 2014, Windermere and associated strata in the Stibnite-Edwardsburg area, central Idaho: Geological Society of America Abstracts with Programs, v. 46, no. 6, p. 829.

Linde, G.M., Cashman, P.H., Trexler, J.H., and Dickinson, W.R., 2014, Stratigraphic trends in detrital zircon geochronology of upper Neoproterozoic and Cambrian strata, Osgood Mountains, Nevada, and elsewhere in the Cordilleran miogeocline: Evidence for early Cambrian uplift of the Transcontinental Arch: Geosphere, v. 10, p. 1402–1410, doi:10.1130/GES01048. 1.

Linde, G.M., Trexler, J.H., Cashman, P.H., Gehrels, G., and Dickinson, W.R., 2016, Detrital zircon U-Pb geochronology and Hf isotope geochemistry of the Roberts Mountains allochthon: New insights into the early Paleozoic tectonics of western North America: Geosphere, v. 12, p. 1016–1031, doi:10.1130/GES01252.1.

Link, P.K., and Janecke, S.U., 2009, Mantle drip from the rising Lemhi Arch: 500 Ma plutons and detrital zircons in Upper Cambrian Sandstones, eastern Idaho: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 181.

Link, P.K., Jansen, S.T., Halimdihardja, P., Lande, A., and Zahn, P., 1987, Stratigraphy of the Brigham Group (Late Proterozoic–Cambrian), Bannock, Portneuf, and Bear River Ranges, southeastern Idaho, *in* Miller, W.R., ed., The thrust belt revisited: Wyoming Geological Association 38th Annual Field Conference Guidebook, p. 133–148.

Link, P.K., et al., 1993, Middle and Late Proterozoic stratified rocks of the western U.S. Cordillera, Colorado Plateau, and Basin and Range Province, *in* Reed, J.C., et al., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 463–595, doi:10.1130/DNAG-GNA-C2.463.

Link, P.K., Fanning, C.M., and Beranek, L.P., 2005, Reliability and longitudinal change of detrital-zircon age spectra in the Snake River system, Idaho and Wyoming: An example of reproducing the bumpy barcode: Sedimentary Geology, v. 182, p. 101–142, doi:10.1016/j.sedgeo.2005.07.012.

Link, P.K., Fanning, C.M., Lund, K.I., and Aleinikoff, J.N., 2007, Detrital zircons, correlation and provenance of Mesoproterozoic Belt Supergroup and correlative strata of east-central Idaho and southwest Montana, *in* Link, P.K., and Lewis, R.S., eds., Proterozoic geology of western North America and Siberia: SEPM (Society for Sedimentary Geology) Special Publication 86, p. 101–128, doi:10.2110/pec.07.86.0101.

Link, P.K., Stewart, E.D., Steel, T., Sherwin, J.-A., Hess, L.T., 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 the Mesoproterozoic Earth: Geological Society of America Special Paper 522, doi:10.1130/2016.2522(07).

Link, P.K., Autenrieth-Durk, K.M., Cameron, A., Fanning, C.M., Vogl, J.J., and Foster, D.A., 2017, U-Pb zircon ages of the Wildhorse Gneiss Complex, Pioneer Mountains, south-central Idaho and tectonic implications: Geosphere, v. 13, p. 681–698, doi:10.1130/GES01418.1.

Lister, G.S., Etheridge, M.A., and Symonds, P.A., 1986, Detachment faulting and the evolution of passive continental margins: Geology, v. 14, p. 246–250, doi:10.1130/0091-7613(1986)14<246:DFATEO>2.0.CO;2.

Lochman-Balk, C., 1971, The Cambrian of the craton of the United States, *in* Holland, C.H., ed., Cambrian of the new world: New York, Wiley Interscience, p. 79–168.

Lochman-Balk, C., 1974, Late Dresbachian (Late Cambrian): Biostratigraphy of North America: Geological Society of America Bulletin, v. 85, p. 135–140, doi:10.1130/0016-7606(1974)85<135:LDLCBO>2.0.CO;2.

Ludwig, K.R., 2003, Isoplot/Ex 3.00: A geochronological toolkit for Microsoft Excel: Berkeley, Berkeley Geochronology Center Special Publication 4, 70 p.

Lund, K., 2008, Geometry of the Neoproterozoic and Paleozoic rift margin of western Laurentia: Implications for mineral deposit settings: Geosphere, v. 4, p. 429–444, doi:10.1130/GES00121.1.

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, 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, p. 430–453, doi:10.1130/B26565.1.

Ma, Chong, Bergeron, P., Foster, D.A., Dutrow, B.L., Mueller, P.A., and Allen, C., 2016, Detrital-zircon geochronology of the Sawtooth metamorphic complex, Idaho: Evidence for metamorphosed lower Paleozoic shelf strata within the Idaho batholith: Geosphere, v. 12, p. 1136–1153, doi:10.1130/GES01201.1.

Mahoney, J.B., Link, P.K., and Yonkee, W.A., 2015, Neoproterozoic–Cambrian tectonic evolution of the northern Rocky Mountains: The dynamics of rifting along western Laurentian Margin: Geological Society of America Abstracts with Programs, v. 46, no. 6, p. 763.

Malone, D.H., Craddock, J.P., and Kenderes, S., 2017, Detrital zircon geochronology and provenance of the Middle Cambrian Flathead Sandstone, Park County, Wyoming: The Mountain Geologist, v. 54, p. 86–103.

May, S.R., Gray, G.G., Summa, L.L., Stewart, N.R., Gehrels, G.E., and Pecha, M.E., 2013, Detrital zircon geochronology from the Bighorn Basin, Wyoming, U.S.A.: Implications for tectonostratigraphic evolution and paleogeography: Geological Society of America Bulletin, v. 125, p. 1403–1422, doi:10.1130/B30824.1.

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.

Middleton, L.T., Steidtmann, J.R., and DeBour, D.A., 1980, Stratigraphy and depositional setting of some Middle and Upper Cambrian rocks, Wyoming: Wyoming Geological Association 31st Annual Field Conference Guidebook, p. 23–35.

Muehlberger, W.R., 1983, Tectonic map of North America: American Association of Petroleum Geologists, scale 1:5,000,000.

Myrow, P.M., Taylor, J.F., Runkel, A.C., and Ripperdan, R.L., 2012, Mixed siliciclastic-carbonate upward-deepening cycles of the upper Cambrian inner detrital belt of Laurentia: Journal of Sedimentary Research, v. 82, p. 216–231, doi:10.2110/jsr.2012.20.

Oriel, S.S., and Platt, L.B., 1980, Geologic map of the Preston 1° by 2° quadrangle, southeastern Idaho and western Wyoming: U.S. Geological Survey Map I-1127, scale 1:250,000.

Palmer, A.R., 1971, The Cambrian of the Great Basin and adjacent areas, western United States, *in* Holland, C.H., ed., Cambrian of the New World: New York, Wiley Interscience, p. 1–78.

Pearson, D.M., Link, P.K., Todt, M.K., Hansen, C.M., Krohe, N.J., and Mahoney, J.B., 2016, The Lemhi Arch of east-central Idaho: A stranded fault block within the western Laurentian rift margin: Geological Society of America Abstracts with Programs, v. 48, no. 6, doi:10.1130/abs/2016RM-276022.

Ross, C.P., 1947, Geology of the Borah Peak quadrangle, Idaho: Geological Society of America Bulletin, v. 58, p. 1085–1160, doi:10.1130/0016-7606(1947)58[1085:GOTBPQ]2.0.CO;2.

Ruppel, E.T., 1986, The Lemhi Arch: A Late Proterozoic and early Paleozoic landmass in central Idaho, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 119–130, doi:10.1306/M41456C6.

Saltzman, M.R., Runnegar, B., and Lohman, K.C., 1998, Carbon-isotope stratigraphy of the Pterocephaliid biomere in the eastern Great Basin: Record of a global oceanographic event during the Late Cambrian: Geological Society of America Bulletin, v. 110, p. 285–297, doi:10.1130/0016-7606(1998)110<0285:CISOUC>2.3.CO;2.

Saltzman, M.R., Cowan, C.A., Runkel, A.C., Runnegar, B., Stewart, M.C., and Palmer, A.R., 2004, The Late Cambrian SPICE event and the Sauk II-Sauk III regression: New evidence from Laurentian basins in Utah, Iowa, and Newfoundland: Journal of Sedimentary Research, v. 74, p. 366–377, doi:10.1306/120203740366.

Saltzman, M.R., Young, S.A., Kump, L.R., Gill, B.C., Lyons, T.W., and Runnegar, B., 2011, Pulse of atmospheric oxygen during the Late Cambrian: Proceedings of the National Academy of Sciences of the United States of America, v. 108, p. 3876–3881, doi:10.1073/pnas.1011836108.

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, doi:10.1130/0016-7606(1957)68[151:PEOTGM]2.0.CO;2.

Scholten, R., and Ramspott, L.D., 1968, Tectonic mechanisms indicated by structural framework of central Beaverhead Range, Idaho-Montana: Geological Society of America Special Paper 104, 71 p., doi:10.1130/SPE104.

Skipp, B., 1984, Geologic map and cross sections of the Italian Peak and Italian Peak Middle roadless areas, Beaverhead County, Montana and Clark and Lemhi Counties, Idaho: U.S. Geological Survey Miscellaneous Field Studies Map MF-1601-B, scale 1:62,500.

Skipp, B., and Link, P.K., 1992, Middle and late Proterozoic rocks and late Proterozoic tectonics in the southern Beaverhead Mountains, Idaho and Montana: A preliminary report, *in* Link, P.K., et al., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 141–154, doi:10.1130/MEM179-p141.

Sloss, L.L., 1950, Paleozoic sedimentation in Montana area: American Association of Petroleum Geologists Bulletin, v. 34, p. 423–451.

Sloss, L.L., 1954, Lemhi Arch, a mid-Paleozoic positive element in south-central Idaho: Geological Society of America Bulletin, v. 65, p. 365–368, doi:10.1130/0016-7606(1954)65[365:LAAMPE]2.0.CO;2.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, p. 93–114, doi:10.1130/0016-7606(1963)74[93:SITCIO]2.0.CO;2.

Sloss, L.L., 1988, Tectonic evolution of the craton in Phanerozoic time, *in* Sloss, L.L., ed., Sedimentary cover–North American craton: U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. D-2, p. 25–51, doi:10.1130/DNAG-GNA-D2.25.

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

Thomas, R.C., 1993, The Marjumiid-Pterocephaliid (Upper Cambrian) mass extinction event in the western United States [Ph.D. thesis]: Seattle, University of Washington, 352 p.

Thomas, R.C., 1994, The timing of the Sauk II-Sauk III (Upper Cambrian) unconformity in the western United States: Geological Society of America Abstracts with Programs, v. 26, no. 6, p. 122.

Thomas, R.C., 1995, Cambrian mass extinction ("biomere") boundaries: A summary of thirty years of research: Northwest Geology, v. 24, p. 67–75.

Thomas, R.C., 2007, A field guide to the Cambrian section at Camp Creek, southwest Montana: Northwest Geology, v. 36, p. 231–244.

Thomas, R.C., and Roberts, S., 2007, A summary of the stratigraphy and depositional setting of Paleozoic rocks in the Dillon area: Northwest Geology, v. 36, p. 35–56.

Thomas, W.A., 1977, Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: American Journal of Science, v. 277, p. 1233–1278, doi:10.2475/ajs.277.10.1233.

Thomas, W.A., 2014, A mechanism for tectonic inheritance at transform faults of the Iapetan margin of Laurentia: Geoscience Canada, v. 41, p. 321–344, doi:10.12789/geocanj.2014.41.048.

Todt, M.K., 2014, U-Pb and Hf Isotopic analysis of zircon grains from the Nounan Dolomite and Worm Creek Quartzite, Idaho and their potential magmatic source: Implications for Cambrian Laurentian tectonics [M.S. thesis]: Pocatello, Idaho State University, 166 p.

Todt, M.K., and Link, P.K., 2013, Sedimentary provenance of the Upper Cambrian Worm Creek Quartzite, Idaho, using U-Pb and Lu-Hf isotopic analysis of zircon grains: Northwest Geology, v. 42, p. 293–298.

Trimble, D.E., and Carr, W.M., 1976, Geology of the Rockland and Arbon quadrangles, Power County, Idaho: U.S. Geological Survey Bulletin 1399, 115 p.

Vuke, S.M., Porter, K.W., Lonn, J.D., and Lopez, D.A., 2007, Geologic map of Montana: Montana Bureau of Mines and Geology Map GM-62, scale 1:500,000.

Wakeley, L.D., 1975, Petrology of the upper Nounan–Worm Creek Sequence, Upper Cambrian Nounan and St. Charles Formations, southeast Idaho [M.S. thesis]: Logan, Utah State University, 127 p.

Walcott, C.D., 1908, Nomenclature of some Cambrian Cordilleran formations: Smithsonian Miscellaneous Collections, v. 53, p. 1–12.

Wulf, T.D., 2011, Sequence stratigraphy and detrital zircon geochronology of the Swan Peak Quartzite, southeastern Idaho [M.S. thesis]: College Station, Texas A&M University, 116 p.

Yates, R.G., 1968, The trans-Idaho discontinuity, *in* International Geological Congress, 23rd: Prague, Academy of Sciences of the Czech Republic, p. 117–123.

Yonkee, W.A., Dehler, C.D., Link, P.K., Balgord, E.A., Keeley, J.A., Hayes, D.S., Wells, M.L., Fanning, C.M., and Johnston, S.M., 2014, Tectono-stratigraphic framework of Neoproterozoic to Cambrian strata, west-central U.S.: Protracted rifting, glaciation, and evolution of the North American Cordilleran margin: Earth-Science Reviews, v. 136, p. 59–95, doi:10.1016/j.earscirev.2014.05.004.

Zoleikhaei, Y., Frei, D., Morton, A., and Zamanzadeh, S.M., 2016, Roundness of heavy minerals (zircon and apatite) as a provenance tool for unraveling recycling: A case study from the Sefidrud and Sarbaz rivers in N and SE Iran: Sedimentary Geology, v. 342, p. 106–117, doi:10.1016/j.sedgeo.2016.06.016.

MANUSCRIPT RECEIVED 17 APRIL 2017
REVISED MANUSCRIPT RECEIVED 5 JULY 2017
MANUSCRIPT ACCEPTED 14 AUGUST 2017

Printed in the USA