

## Article

# U-Pb LA-ICP-MS Zircon Dating of Crustal Xenoliths: Evidence of the Archean Lithosphere Beneath the Snake River Plain

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**Abstract:** New U-Pb zircon ages are reported for granulite facies crustal xenoliths brought to the surface by mafic lavas in the Snake River Plain. All samples yield Meso-to-Neoproterozoic ages (2.4–3.6 Ga) that significantly expand the known extent of the Archean Wyoming Craton at least as far west as the west-central Snake River Plain. Most zircon populations indicate multiple growth episodes with complexity increasing eastward, but they bear no record of major Phanerozoic magmatic episodes in the region. To extrapolate this work further west to the inferred craton boundary, zircons from southwestern Idaho batholith granodiorites were also analyzed. Although most batholith zircons record Cretaceous formation ages, all samples have zircons with inherited cores—with some recording Proterozoic ages (approaching 2 Ga). These data enhance our perspectives regarding lithosphere architecture beneath southern Idaho and adjacent areas and its possible influence on Cenozoic magmatism associated with the Snake River Plain–Yellowstone “melting anomaly”.

**Keywords:** Archean; Wyoming Craton; crustal xenolith; zircon U-Pb dating



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## 1. Introduction

The North American continental lithosphere is a complex amalgamation of diverse tectonic terranes of Archean to Phanerozoic age cf. [1,2]. In the northern Rocky Mountains, differences in the ages and compositions of these lithospheric blocks are reflected in the composition and style of Cenozoic magmatism and related tectonic evolution of the crust (e.g., [3–5]). Important questions concern the extent to which magmatic compositions are inherited from or altered by interaction with lithospheric crust and mantle domains and, conversely, how the lithosphere may be modified by ensuing magmatic processes. Understanding the relative influence of lithospheric vs. deeper mantle processes on the geologic development of this region requires an improved understanding of the architecture and history of the continental lithosphere, which is hard to come by owing to limited basement exposures and/or inherent structural complexity.

## 2. Geological Background

Notably, the westernmost parts of cratonic North America are largely obscured by the extensive Idaho batholith, by volcanic and sedimentary rocks of the western Snake River Plain (SRP), by outliers of Columbia River basalt, and by a variety of Phanerozoic and Proterozoic supracrustal rocks. The location of the western margin of the craton has been inferred on the basis of an  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic isopleth—the so-called ‘0.706 line’—as measured in Mesozoic granitoid rocks [6–10] and also in Neogene volcanic rocks [11]. To the east of this line in southern Idaho (Figure 1), both silicic and mafic volcanic rocks of the SRP are characterized by initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios greater than 0.706, whereas, to the west, initial ratios are systematically lower (most < 0.7045). This compositional transition is



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sharp (within only tens of km in places) and corresponds closely with a profound tectonic boundary—the western Idaho suture zone (WISZ)—that separates Paleozoic and Mesozoic accreted ‘oceanic’ or ‘juvenile’ terranes to the west from older ‘cratonic’ rocks to the east. This boundary also corresponds to conspicuous eastward decreases in Bouguer gravity and aeromagnetic intensity [12], reflecting a gross compositional lateral discontinuity in the crust.

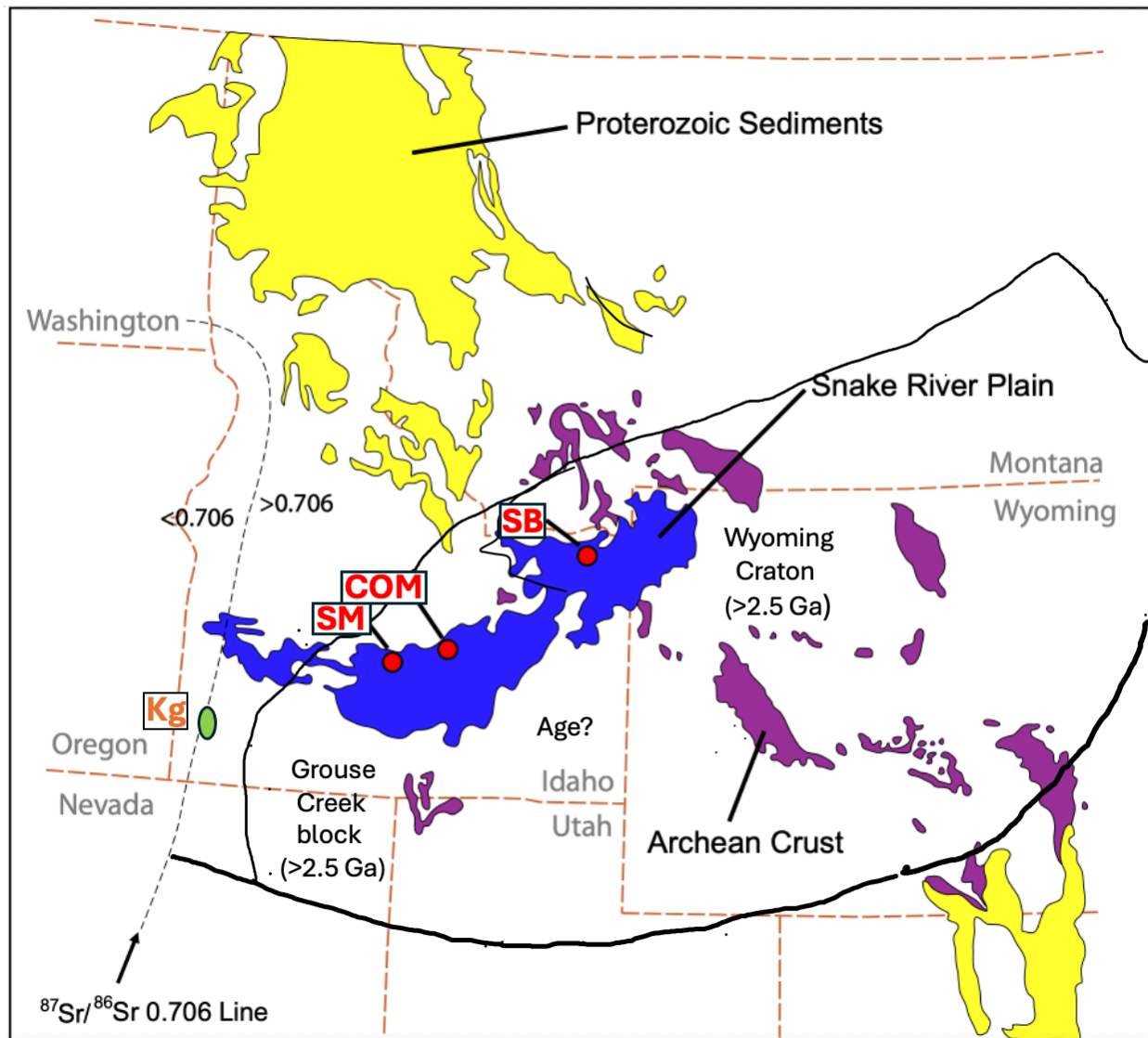


**Figure 1.** Locations are shown for analyzed crustal xenoliths (red circles) from Swan Butte (SB), Craters of the Moon (COM), and Square Mt. (SM), and Cretaceous granodiorites (Kg; green oval) of the Owyhee Mtns. Estimated extent of Archean terranes of the Wyoming Craton and Grouse Creek block are from [13]; approximate extent of Archean crust is denoted by the heavy black line to the south and the lighter (less precise) line to the north. Maximum age of the crust beneath SE Idaho is unknown. Western limit of the craton is approximated by the dashed ‘0.706 line’. Actual outcroppings of known Archean basements are shown in purple patches. The Snake River Plain-Yellowstone (SRPY) volcanic track (ca. 14–0 Ma) is shown in blue.

The geochronology of the exposed basement to the east was reviewed by [13], and [14] reported ages of ‘inherited’ zircons in Idaho batholith exposures north of the SRP to infer the distribution of old basement rocks at depth. The oldest exposed crust consists of igneous and metasedimentary rocks of the Archean Wyoming Craton (Figure 1). Archean

crust is also exposed in ranges south of (e.g., Albion [Idaho], Raft River/Grouse Creek [Utah], and East Humboldt Mtns. [N. Nevada]) and north of (e.g., Tobacco Root, Galletin, and Beartooth Mtns. [Montana]) the SRP cf. [13,15–22]. The SRP comprises Miocene to Quaternary rhyolitic and basaltic volcanic manifestations of the Yellowstone “hotspot track” cf. [23,24]. Pb-Sr-Nd-Hf isotopic compositions of SRP volcanic rocks, e.g., [11,25,26], are consistent with extrapolation of Archean terranes as far west as the 0.706 line. North and south of this postulated Archean salient, the cratonic basement appears to be dominantly of Meso- to Neoproterozoic age based on dating of limited exposures, inheritance of old zircons in a variety of younger igneous rocks, e.g., [14,22,27,28], and Nd-isotope model ages [29] in younger plutons. At present, boundaries between and complexities within crustal domains in this region are poorly constrained.

Occurrences of gneissic crustal xenoliths in certain SRP lavas afford an opportunity to directly date the underlying basement in areas where such rocks are not exposed at the surface. Compositions of the xenoliths are consistent with both igneous and sedimentary protoliths; all have been metamorphosed to granulite grade under deep crustal conditions [30,31]. Whole rock Sr-Nd-Pb isotopic compositions of samples from three localities [32,33] demonstrate that (1) some xenoliths are U-poor and have highly unradiogenic Pb isotopic compositions similar to those of Archean ore leads [34], (2) most scatter along a Neoarchean  $^{207}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$  secondary isochron (~2.6 Ga), and (3) many lie along a Neoarchean Sm-Nd isochron (~2.8 Ga). The isotopic data combined with low U and Rb contents suggest that many of these xenoliths must represent the Archean lower crust, and the implied ages suggest a close affinity with the Wyoming Craton. Precise dating of the bulk rocks is hindered by heterogeneity in initial isotopic compositions and uncertain petrogenetic affinities between diverse xenoliths from each locality. To refine the ages, four mafic to felsic xenoliths were selected for U-Pb zircon geochronology.

### 3. Materials and Methods

The xenolith samples studied come from three localities (Figure 1) along the northern margin of the SRP: Square Mountain in the west (DM-103), Craters of the Moon lava field (COM-9A and COM-22), and Swan Butte cinder cone (Spencer/Kilgore volcanic field) to the east (SK-3). DM-103 is a granulite-facies hypersthene granodiorite (opdalite) containing 73.8%  $\text{SiO}_2$ . The rock is gneissic with abundant microlite-bearing brown glass, presumably produced by heating proximal to an underlying silicic magma system or during transport to the surface; original mafic minerals are poorly preserved. Such xenoliths are large (commonly more than 0.5 m in diameter) and locally abundant in the hybrid host lava [35]. COM-9A is also an opdalite with 73.1%  $\text{SiO}_2$ , whereas COM-22 is an orthopyroxene-bearing granitoid rock (enderbite) with 68.5%  $\text{SiO}_2$ ; both were collected from the ferrolatitic Devils Orchard lava flow [36]. SK-3 is a hypersthene diorite (norite) containing 54.9%  $\text{SiO}_2$ ; the host lava is an evolved basalt. All xenoliths were subjected to granulite facies metamorphism at temperatures above 700–750 °C as evidenced by anhydrous mineral assemblages and mineral thermometry (plagioclase-K feldspar and/or ilmenite-magnetite; [31]). Host lavas for the xenoliths have ages of ca. 3.6 Ma, 2 Ka, and <700 Ka, respectively.

Because basement xenoliths so far have not been found in westernmost Idaho, samples of Cretaceous Idaho batholith granitoids cf. [6,37,38] were collected from the Owyhee Mountains (Figure 1) with the goal of establishing minimum basement ages proximal to the  $^{87}\text{Sr}/^{86}\text{Sr}$  0.706 line via inheritance in their zircons. Three samples were selected for study, including two biotite-hornblende ‘I-type’ granodiorites and one biotite-muscovite ‘S-type’ granite; initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in each body exceed 0.706 [38].

Zircons were separated by standard methods. Following gentle hand-crushing of coarse powders by mortar and pestle, samples were sieved to <350  $\mu\text{m}$ , and minerals were separated using magnetic and heavy-liquid methods. Zircons were individually hand-picked and then mounted for analysis along with in-house standard zircon grains from Rio de Peixe, Brazil [39], and Duluth anorthositic gabbro FC-1 [40]. Cathodoluminescence (CL)

images at 200–300 $\times$  magnification were used to characterize internal zoning and to aid in selecting spots for analysis (Figure 2).

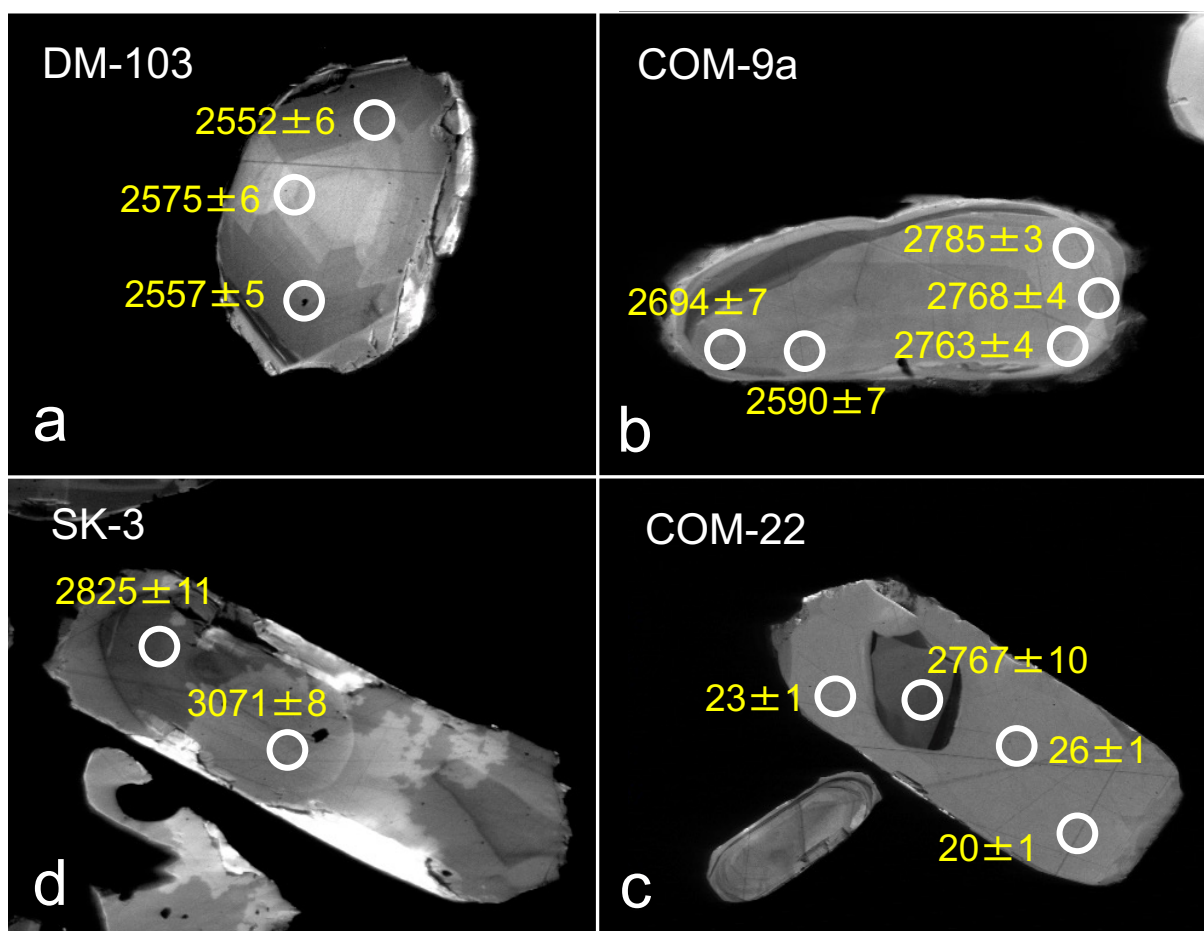


**Figure 2.** Cathodoluminescence images are shown for selected polished zircon grains from each of the analyzed xenoliths. White circles show representative analysis spots ( $\sim 30\ \mu\text{m}$  diameter) with resulting  $^{207}\text{Pb}/^{206}\text{Pb}$  dates in Ma. Results are shown for representative  $^{207}\text{Pb}/^{206}\text{Pb}$  ages. (a) Sample DM-103. A representative near-homogeneous grain; all grain analyses have an average  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $2565 \pm 13\ \text{Ma}$  ( $n = 37$ ). (b) Sample COM-9. A fairly representative grain. This sample has two prominent  $^{207}\text{Pb}/^{206}\text{Pb}$  age groupings averaging  $2747 \pm 30\ \text{Ma}$  ( $n = 20$ ) and  $3210 \pm 33\ \text{Ma}$  ( $n = 5$ ), with a single outlier age of  $3568\ \text{Ma}$ . (c) Sample COM-22. Core age of grain is representative of more than half the analyzed grains, averaging  $2757 \pm 22\ \text{Ma}$  ( $n = 15$ ), with slightly younger groups of  $2656 \pm 40\ \text{Ma}$  ( $n = 6$ ) and  $2457 \pm 15\ \text{Ma}$  ( $n = 4$ ). Bright edges of the illustrated grain correspond to youthful zircon overgrowths ( $20\text{--}26\ \text{Ma}$ ). (d) Sample SK-3. Slightly heterogeneous zircon with bracketing  $^{207}\text{Pb}/^{206}\text{Pb}$  ages averaging  $3142 \pm 61\ \text{Ma}$  ( $n = 9$ ), and  $2770 \pm 35\ \text{Ma}$  ( $n = 7$ ), with a single intermediate age of  $2914\ \text{Ma}$ .

Analyses were carried out using a NewWave© (Fremont, CA, USA) Nd-YAG 213 nm laser ablation system connected to a ThermoFinnigan© (Waltham, MA, USA) Element 2 High Resolution-Inductively Coupled Plasma-Mass Spectrometer, essentially following the methodology of [10]. Operating parameters for the laser include 8 s warm up, 16 s delay to acquire blank or background measurements, 46 s dwell time, and  $30\ \mu\text{m}$  diameter spot size. Data were collected in 300 sweeps across the mass range 202–238, which includes isotopes of Hg, Pb, Th, and U. All data were corrected for mass fractionation based on analyses of standards. For example, for FC-1, true values are taken as:  $^{207}\text{Pb}/^{235}\text{U} = 1.951607$ ,  $^{206}\text{Pb}/^{238}\text{U} = 0.185877$ ,  $^{207}\text{Pb}/^{206}\text{Pb} = 0.076149$ , and age =  $1099\ \text{Ma}$ ; For Peixe, true values are taken as:  $^{207}\text{Pb}/^{235}\text{U} = 0.742660$ ,  $^{206}\text{Pb}/^{238}\text{U} = 0.091430$ ,  $^{207}\text{Pb}/^{206}\text{Pb} = 0.058915$ , and age =  $564\ \text{Ma}$ . The Isoplot 3.0

program [41] was used for data reduction.  $^{207}\text{Pb}/^{235}\text{U}$ ,  $^{206}\text{Pb}/^{238}\text{U}$  and  $^{207}\text{Pb}/^{206}\text{Pb}$  ages were calculated for each analysis spot. Data were discarded if ages were more than 10% discordant. Representative analytical results are displayed graphically (Figure 3), and data are tabulated in Supplemental Materials, Table S1 (xenoliths) and Table S2 (granitoids) for all analyses.

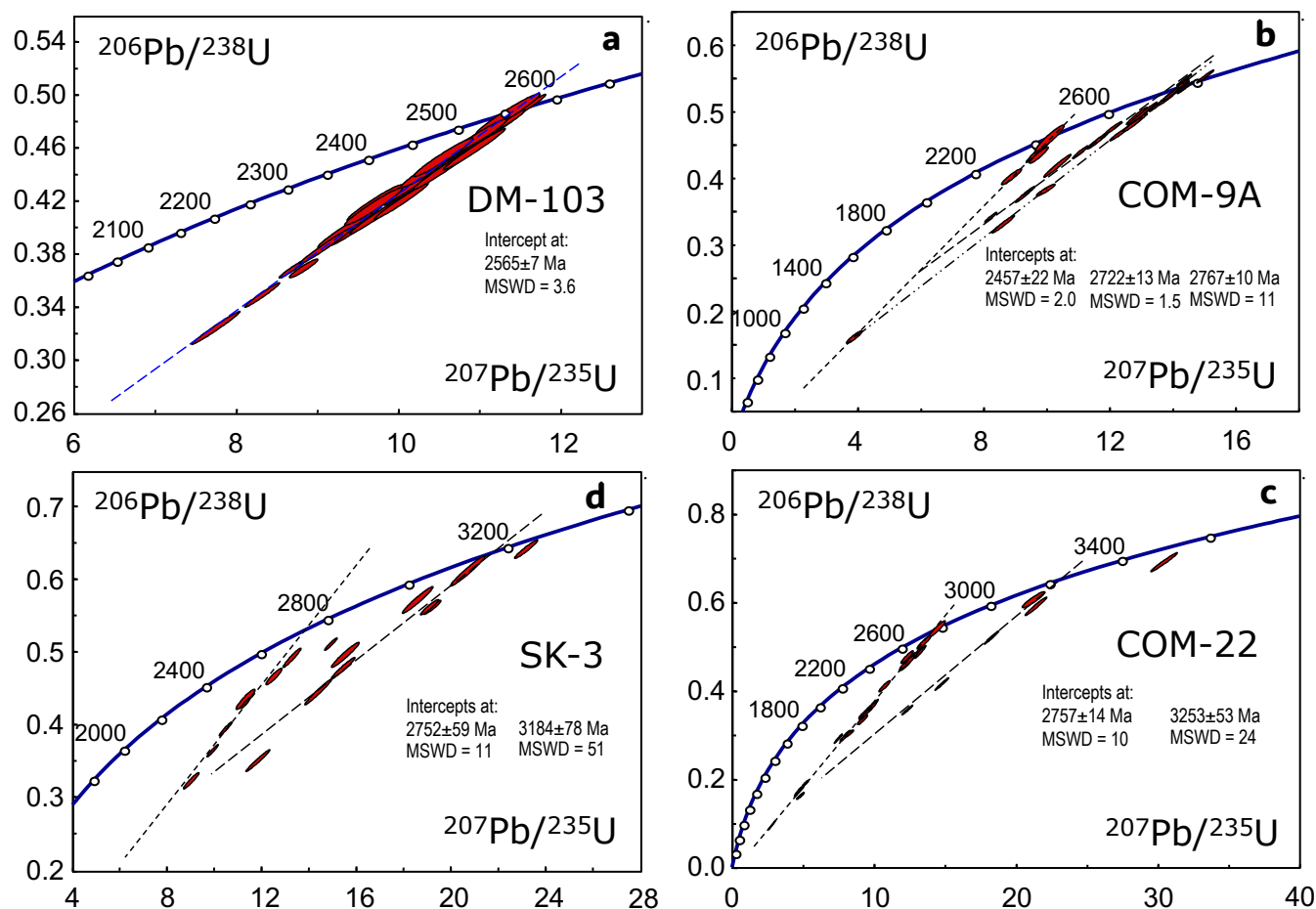


**Figure 3.** Concordia isochron plots show all zircon analyses from each of the denoted samples. The Square Mt. xenolith (DM-103 (a)) has a remarkably homogeneous zircon population, whereas more easterly xenoliths from Craters of the Moon (COM-9A (b), COM-22 (c)) and Swan Butte (SK-3 (d)) have complex populations with outliers ranging to >3.5 Ga.

#### 4. Results

Zircons from SRP xenoliths are highly varied in size, shape, and details of internal zoning and structure, as seen in representative CL grain mount images (Figure 2). DM-103 has the simplest U-Pb systematics. Zircon grains are well- to sub-rounded and range in diameter from 30 to 300  $\mu\text{m}$  (Figure 2a). Thirty-seven analyses from 14 grains yield an average  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $2565 \pm 13$  Ma (Figure 3a). These analyses are highly reproducible; for example, seven laser ablation analyses of a single grain agree within error and provide a weighted mean age of  $2581 \pm 5$  Ma (2 s). DM-103 zircons lack datable overgrowth rims, and all analyses fall along the same discordia line, albeit with an imprecise present-day lower intercept (Figure 3a).

COM-9A zircons have complex dark and light-colored cores with thin overgrowth rims (Figure 2b). Based on 27 analyses from 16 grains, the cores yield late Archean dates (2.8–2.4 Ga), with peak  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of  $2457 \pm 15$ ,  $2757 \pm 22$ , and  $2656 \pm 40$  Ma. Most grains appear to have experienced some recent Pb loss (Figure 3b). Overgrowth rims were too thin for meaningful analysis via laser ablation.

COM-22 zircons also exhibit dark, high-U cores and bright, low-U rims (Figure 2c). Based on 31 analyses on 14 grains, the darker cores yielded Archean dates (3.5–2.7 Ga), with peak  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of  $2747 \pm 30$  and  $3210 \pm 33$  Ma, and one outlier at 3568 Ma. These zircons also appear to have experienced recent Pb loss (Figure 3c). Overgrowths on some grains were wide enough to analyze and consistently yielded  $^{238}\text{U}/^{206}\text{Pb}$  ages near 20–30 Ma, albeit with large uncertainty owing to both low concentrations of U and radiogenic Pb and difficulty in applying common Pb corrections using LA-ICP-MS [39].

SK-3 zircons exhibit the most complex morphologies, with variably shaded cores and bright, low-U overgrowths (Figure 2d). Based on 17 analyses of 11 grains, the darker cores yield Archean dates (3.3–2.7 Ga), with apparent peak  $^{207}\text{Pb}/^{206}\text{Pb}$  age populations of  $2770 \pm 35$  and  $3142 \pm 61$  Ma. A core in one grain records a lone date near 3.3 Ga. These zircons also exhibit recent Pb loss (Figure 3d).

Finally, most zircons from the Idaho batholith granitoids of the Owyhee Mtns. are euhedral to subhedral, although complexly zoned cores occur in populations from the biotite granodiorites. Previously reported U-Pb analyses [38] were specifically aimed at dating late-formed rims of zircons in plutons from this area and largely avoided the issue of inheritance of earlier-formed zircon. In our study, 74 analyses were made on 57 grains, with a primary emphasis on the cores. The majority of  $^{238}\text{U}/^{206}\text{Pb}$  dates are Cretaceous, with most clustering between ~85–90 and ~95–109 Ma. However, cores of two grains in sample 07DU-02 yielded approximate Paleo-Mesoproterozoic dates (1.9 and 1.4 Ga). Two grains in sample 07DU-12 yielded similar  $^{207}\text{Pb}/^{206}\text{Pb}$  dates (1.7 and 1.2 Ga), albeit with considerable discordance. These data are consistent with the incorporation of early Paleo-Mesoproterozoic material in some of these granitic rocks cf. [14] and suggest the presence of a basement at least this old beneath southwestern Idaho.

## 5. Discussion

Although of a reconnaissance nature, this study bears on two significant questions: (1) the areal distribution of Archean basement and overall architecture of continental lithosphere, and (2) the apparent resilience of Archean crust in the face of profound Phanerozoic tectonic and magmatic evolution of the interior northwestern United States.

Despite the fact that complex zoning is typical of zircons from most of the xenoliths studied so far, the xenolith data record a spectrum of igneous and/or metamorphic events that is virtually restricted to the Archean. Some samples exhibit a broad span of apparent zircon dates ranging mainly between 3.3–2.6 Ga, with no distinct modality. The youngest apparent dates observed in the xenoliths are ca. 2.4 Ga. Similar age spectra are observed in exposed basement terranes of the Wyoming Craton (cf. papers in the 2006 Canadian Journal of Earth Sciences Special Issue on the Wyoming Province; e.g., [13]). Notably, dates for the Craters of the Moon xenoliths overlap dates (2.67–2.60 Ga) obtained for the oldest components of the allochthonous Wildhorse gneiss in the nearby Pioneer Mtns. [22]. Collectively, the xenoliths provide compelling evidence for the westward extension of the Wyoming Province terrane beneath the eastern and central Snake River Plain. Similar granulite xenoliths have been observed in lavas as far west as the Mountain Home area (~115.69° W), but because these are rare and very small, they have not been analyzed.

It remains to be established whether or not true Archean basement extends all the way to the cratonic western margin. There are numerous indications that the Proterozoic basement may extend to the western margin north and south of the SRP cf. [13,28], and our data from the Owyhee Mountains support this interpretation. However, the loci of contacts or sutures between Archean and younger basement terranes remain poorly defined, except as inferred from the distribution of isotopic compositions of Mesozoic and younger magmatic rocks. Notably, many samples of the Idaho Batholith (especially in the southern part or Atlanta lobe) carry inherited zircons of Mesoproterozoic to Archean age [14,28]. These data imply the presence of old (ca. 2.4–3.5 Ga) lithosphere north of the SRP, beneath westernmost Idaho. Interpretation of the latter data is complicated by petrogenetic uncertainties and the fact that many older plutons have been laterally

displaced by tectonic processes associated first with Mesozoic contraction and then by Cenozoic Basin and Range extension cf. [42–45].

Significantly, the xenolith zircons display no record of accretionary events associated with the assembly of younger cratonic blocks. Proterozoic and younger accretionary and contractional tectonism cf. [46] apparently did not impose a significant thermal impact on the Archean crust that they represent. Particularly surprising is the absence in the xenolith zircons of any evidence of the profound late Cretaceous regional plutonism that produced the voluminous Idaho and Boulder batholiths [10,28,47]. This magmatism is thought to reflect crustal anatexis in response to crustal thickening coeval with the ca. 75–100 Ma Sevier orogeny, e.g., [48–51], perhaps coupled with the input of mantle-derived mafic magma [52].

There is also no record in the xenoliths of widespread Eocene (Challis) extensional volcanism and related plutonism or of voluminous mid-Miocene and younger silicic volcanism associated with the SRPY hotspot track. The formation of thin zircon overgrowths (at ca. 20–30 Ma) in some xenoliths does not correspond to any recognized widespread igneous, metamorphic, or tectonic events, although late Oligocene deformation has been documented locally (e.g., Grouse Creek/Raft River ranges; [53]), and remnants of Oligocene (20–26 Ma) Salmon Creek volcanics occur in the Owyhee Mtns. of southwestern Idaho [37]. Moreover, preliminary Hf isotopic data show that zircon overgrowths consist entirely of recycled Archean components; there appear to be no significant open system contributions of more juvenile material [54].

At the Square Mt. locality, the host lava rests directly on a dissected erosion surface on Idaho batholith granitoid rocks, yet the xenolith population consists entirely of high-grade gneissic blocks and fragments; virtually no granitoid xenoliths have been identified. The plutonic rocks could have intruded as sills or diapirs within the mid- to upper crust such that they overlie a granulite basement, or they may represent tectonic slivers that were decapitated from their deeper magmatic roots and thrust eastward over the metamorphic basement. The fact that zircons from crustal xenolith DM-103 show no thermal impact coeval with Idaho batholith plutonism supports an interpretation that the granitic rocks may be allochthonous.

It appears that some, perhaps extensive, parts of the cratonic crust remained isolated and unaffected by external events since the waning phases of craton formation (ca. 2.4 Ga). Perhaps parts of the lithospheric mantle behave in this manner as well, attesting to the perseverance of cratons. An important question concerns the physical thickness of the craton. If it is as thick beneath the Snake River Plain and Yellowstone as estimated for other Archean cratons to the east (i.e., >150–200 km; cf. [13,55,56]), the lithospheric lid could impede and perhaps prevent decompression melting of upwelling mantle plumes, thereby casting doubt on a plume origin for the SRPY melting anomaly [57]. Conversely, if the present-day lithosphere has been thinned sufficiently (to  $\leq$  ~100 km; cf. [58]) to allow decompression melting of a rising mantle plume, the processes responsible for attenuation are unclear, and it is remarkable that there is no obvious evidence for such events recorded in the chronology of the xenoliths or in age-correlative outcrops in the region. However, the current picture is based on a few samples, and there is a clear need for further research.

## 6. Conclusions

The main conclusions from this study are as follows: (1) Archean-aged rocks are present in the middle to upper crust underlying the central and eastern Snake River Plain and preserve varying degrees of complexity in zircon morphology and recorded magmatic histories, and (2) crustal xenoliths, where available, provide direct constraints on age and composition of the underlying crust where surface exposures are not available. What is unclear is the perspective on the present-day depths to which ancient cratonic material (including lithospheric mantle) extends. This is perhaps best evaluated on the basis of isotopic tracers (e.g., Sr, Nd, Pb, etc.) in late Cenozoic volcanic rocks across the region. While older plutonic rocks clearly demonstrate the presence of inherited ancient components, they

potentially have been laterally displaced to varying degrees in response to contractional and extensional tectonics since Mesozoic time. Additionally, there is uncertainty regarding the formation of granitoid bodies (e.g., Idaho batholith and younger Challis plutons; cf. [28]) that likely represent extensive melting at crustal depths cf. [49]. Even Miocene and younger silicic volcanics associated with the SRPY melting anomaly are, in part, products of crustal anatexis to a significant degree [5,59]. To better evaluate the lateral distribution of Archean cratonic *mantle* (i.e., lithosphere), isotopic variations in young basaltic lavas likely provide more direct evidence, and regional investigations thereof are warranted [3,60]. However, there remain questions regarding the extent to which the voluminous SRPY basalts derive from the melting of old lithospheric mantle vs. upwelling mantle plume material [59,61–64]. These questions will be reassessed elsewhere.

**Supplementary Materials:** The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/min14060578/s1>. Table S1. Analyses of zircons from crustal xenoliths, Snake River Plain, Idaho; Table S2. Analyses of zircons from Idaho Batholith, Owyhee Mountains, SW Idaho.

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**Data Availability Statement:** The data set is presented directly in the present study as Supplementary Materials; Table S1 (xenoliths) and Table S2 (Idaho batholith).

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**Conflicts of Interest:** The authors declare they have no conflicts of interest.

## References

1. Hoffman, P. United plates of America, the birth of a craton. *Ann. Rev. Earth Planet. Sci. Lett.* **1988**, *16*, 543–603. [\[CrossRef\]](#)
2. Whitmeyer, S.J.; Karlstrom, K.E. Tectonic model for the Proterozoic growth of North America. *Geosphere* **2007**, *3*, 220–259. [\[CrossRef\]](#)
3. Fitton, J.G.; James, D.; Kempton, P.D.; Ormerod, D.S.; Leeman, W.P. The role of lithospheric mantle in the generation of late Cenozoic basic magmas in the western United States. *J. Petrol.* **1988**, 331–349. [\[CrossRef\]](#)
4. Camp, V.E.; Ross, M.E. Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest. *J. Geophys. Res.* **2004**, *109*, B08204. [\[CrossRef\]](#)
5. Bonnichsen, B.; Leeman, W.P.; Honjo, N.; McIntosh, W.C.; Godchaux, M. Miocene silicic volcanism in southwestern Idaho: Geochronology and geochemistry and evolution of the central Snake River Plain. *Bull. Volcanol.* **2008**, *70*, 315–342. [\[CrossRef\]](#)
6. Armstrong, R.L.; Taubeneck, W.H.; Hales, P.O. Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition, Oregon, Washington and Idaho. *Geol. Soc. Am. Bull.* **1977**, *88*, 397–411. [\[CrossRef\]](#)
7. Fleck, R.J.; Criss, R.E. Strontium and oxygen isotopic variations in Mesozoic and Tertiary plutons of central Idaho. *Contrib. Mineral. Petrol.* **1985**, *90*, 291–308. [\[CrossRef\]](#)
8. Manduca, C.A.; Silver, L.T.; Taylor, H.P., Jr.  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{18}\text{O}/^{16}\text{O}$  isotopic systematics and geochemistry of granitoid plutons across a steeply dipping boundary between contrasting lithospheric blocks in western Idaho. *Contrib. Mineral. Petrol.* **1992**, *109*, 355–372. [\[CrossRef\]](#)
9. Fleck, R.J.; Wooden, J.L. Isotopic identification of the Archean/Proterozoic lithospheric boundary in Idaho. *Geol. Soc. Am. Abstr. Prog.* **1997**, *29*, A-70–A-71.
10. Gaschnig, R.M.; Vervoort, J.D.; Lewis, R.S.; McClelland, W.C. Migrating magmatism in the northern US Cordillera: In situ U-Pb geochronology of the Idaho batholith. *Contrib. Mineral. Petrol.* **2010**, *159*, 863–883. [\[CrossRef\]](#)
11. Leeman, W.P.; Oldow, J.S.; Hart, W.K. Lithosphere-scale thrusting in the western U.S. Cordillera as constrained by Sr and Nd isotopic transitions in Neogene volcanic rocks. *Geology* **1992**, *20*, 63–66. [\[CrossRef\]](#)

12. Mankinen, E.A.; Hildenbrand, T.G.; Zientek, M.L.; Box, S.E.; Bookstrom, A.A.; Carlson, M.H.; Larsen, J.C. *Guide to Geophysical Data for the Northern Rocky Mountains and Adjacent Areas, Idaho, Montana, Washington, Oregon, and Wyoming*; U.S. Geological Survey Open-File Report; USGS: Reston, VA, USA, 2004; p. 2004-1413.
13. Foster, D.A.; Mueller, P.A.; Mogk, D.W.; Wooden, J.L.; Vogl, J.J. Proterozoic evolution of the western margin of the Wyoming Craton: Implications for the tectonic and magmatic evolution of the northern Rocky Mountains. *Canad. J. Earth Sci.* **2006**, *43*, 1601–1619. [\[CrossRef\]](#)
14. Gaschnig, R.M.; Vervoort, J.D.; Lewis, R.S.; Tikoff, B. Probing for Proterozoic and Archean crust in the northern U.S. Cordillera with inherited zircon from the Idaho batholith. *Geol. Soc. Am. Bull.* **2013**, *125*, 73–88. [\[CrossRef\]](#)
15. Wright, J.E.; Snoke, A.W. Tertiary magmatism and mylonitization in the Ruby—East Humboldt metamorphic core complex, northeastern Nevada; U-Pb geochronology and Sr, Nd, and Pb isotope geochemistry. *Geol. Soc. Am. Bull.* **1993**, *105*, 935–952. [\[CrossRef\]](#)
16. Egger, A.E.; Dumitru, T.A.; Miller, E.L.; Savage, C.F.I.; Wooden, J.L. Timing and nature of Tertiary plutonism and extension in the Grouse Creek Mountains, Utah. *Int. Geol. Rev.* **2003**, *45*, 497–532. [\[CrossRef\]](#)
17. Premo, W.R.; Howard, K.A.; Castineiras, P. New SHRIMP U-Pb zircon ages and Nd isotopic signatures for plutonism in the northern Ruby—East Humboldt Ranges of NE Nevada: Implications for the timing of Tertiary core complex formation. *Geol. Soc. Am. Abst. Prog.* **2005**, *37*, 359.
18. Mueller, P.; Heatherington, A.; D’Arcy, K.; Wooden, J.; Nutman, A. Contrasts between Sm–Nd and U–Pb zircon systematics in the Tobacco Root batholith, Montana: Implications for the determination of crustal age provinces. *Tectonophysics* **1996**, *265*, 169–179. [\[CrossRef\]](#)
19. Strickland, A.; Miller, E.L.; Wooden, J.L. The timing of Tertiary metamorphism and deformation in the Albion–Raft River–Grouse Creek metamorphic core complex, Utah and Idaho. *J. Geol.* **2011**, *119*, 185–206. [\[CrossRef\]](#)
20. Yonkee, W.A.; Dehler, C.D.; Link, P.K.; Balgord, E.A.; Keeley, J.A.; Hayes, D.S.; Wells, M.L.; Fanning, C.M.; Johnson, S.M. Tectono-stratigraphic framework of Neoproterozoic to Cambrian strata, west-central U.S.: Protracted rifting, glaciation, and evolution of the North American Cordilleran margin. *Earth Sci. Rev.* **2014**, *136*, 59–95. [\[CrossRef\]](#)
21. Link, P.K.; Stewart, E.D.; Steel, T.S.; Sherwin, J.-A.; Hess, L.T.; McDonald, C. Detrital zircons in the Mesoproterozoic upper Belt Supergroup in the Pioneer, Beaverhead and Lemhi Ranges, MT and ID. In *Belt Basin: Window to Meso-Proterozoic Earth*; Maclean, J.S., Sears, J.W., Eds.; Geological Society of America Special Papers; Geological Society of America: Boulder, CO, USA, 2016; Volume 522, pp. 163–183. [\[CrossRef\]](#)
22. Link, P.K.; Autenrieth-Durk, K.M.; Cameron, A.; Fanning, C.M.; Vogl, J.J.; Foster, D.A. U-Pb zircon ages of the Wildhorse gneiss, Pioneer Mountains, south-central Idaho, and tectonic implications. *Geosphere* **2017**, *13*, 68–698. [\[CrossRef\]](#)
23. Christiansen, R.L.; Foulger, G.R.; Evans, J.R. Upper-mantle origin of the Yellowstone hotspot. *Geol. Soc. Am. Bull.* **2002**, *114*, 1245–1256. [\[CrossRef\]](#)
24. Camp, V.E.; Wells, R.E. The case for a long-lived and robust Yellowstone hotspot. *GSA Today* **2021**, *31*, 4–10. [\[CrossRef\]](#)
25. Doe, B.R.; Leeman, W.P.; Christiansen, R.L.; Hedge, C.E. Lead and strontium isotopes and related trace elements as genetic tracers in the Upper Cenozoic rhyolite-basalt association of the Yellowstone Plateau volcanic field. *J. Geophys. Res.* **1982**, *87*, 4785–4806. [\[CrossRef\]](#)
26. Nash, B.P.; Perkins, M.E.; Christensen, J.N.; Lee, D.-C.; Halliday, A.N. The Yellowstone hotspot in space and time: Nd and Hf isotopes in silicic magmas. *Earth. Planet. Sci. Lett.* **2006**, *247*, 143–156. [\[CrossRef\]](#)
27. Shuster, R.D.; Bickford, M.E. Chemical and isotopic evidence for the petrogenesis of the northeastern Idaho batholith. *J. Geol.* **1985**, *93*, 727–742. [\[CrossRef\]](#)
28. Gaschnig, R.M.; Vervoort, J.D.; Tikoff, B.; Lewis, R.S. Construction and preservation of batholiths in the northern U.S. Cordillera. *Lithosphere* **2016**, *9*, 315–324. [\[CrossRef\]](#)
29. Bennett, V.C.; DePaolo, D.J. Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping. *Geol. Soc. Am. Bull.* **1987**, *99*, 674–685. [\[CrossRef\]](#)
30. Leeman, W.P. Deep crustal xenoliths from the Snake River Plain. *EOS Trans. Am. Geophys. Un.* **1979**, *60*, 945.
31. Matty, D.J. Petrology of deep crustal xenoliths from the Eastern Snake River Plain, Idaho. Ph.D. Dissertation, Rice University, Houston, TX, USA, 1984; 273p.
32. Leeman, W.P. Primitive lead in deep crustal xenoliths from the Snake River Plain, Idaho. *Nature* **1979**, *281*, 365–366. [\[CrossRef\]](#)
33. Leeman, W.P.; Menzies, M.A.; Matty, D.J.; Embree, G.F. Strontium, neodymium and lead isotopic compositions of deep crustal xenoliths from the Snake River Plain: Evidence for Archean basement. *Earth. Planet. Sci. Lett.* **1985**, *75*, 354–368. [\[CrossRef\]](#)
34. Stacey, J.S.; Kramers, J.D. Approximation of terrestrial lead evolution by a two-stage model. *Earth. Planet. Sci. Lett.* **1975**, *26*, 207–221. [\[CrossRef\]](#)
35. Honjo, N.; Leeman, W.P. Origin of hybrid ferrolatite lavas from the Magic Reservoir eruptive center, Snake River Plain, Idaho. *Contrib. Mineral. Petrol.* **1987**, *96*, 163–177. [\[CrossRef\]](#)
36. Leeman, W.P.; Vitaliano, C.J.; Prinz, M. Evolved lavas from the Snake River Plain: Craters of the Moon National Monument, Idaho. *Contrib. Mineral. Petrol.* **1976**, *56*, 35–60. [\[CrossRef\]](#)

37. Norman, M.D.; Leeman, W.P. Geochemical evolution of Cenozoic-Cretaceous magmatism and its relation to tectonic setting, southwestern Idaho, USA. *Earth. Planet. Sci. Lett.* **1989**, *94*, 78–96. [\[CrossRef\]](#)
38. Benford, B.; Crowley, J.; Schmitz, M.; Northrup, C.J.; Tikoff, B. Mesozoic magmatism and deformation in the northern Owyhee Mountains, Idaho: Implications for along-zone variations for the western Idaho shear zone. *Lithos* **2010**, *2*, 93–118. [\[CrossRef\]](#)
39. Chang, Z.; Vervoort, J.D.; McClelland, W.C.; Knaack, C. U-Pb dating of zircons by LA-ICP-MS. *Geochim. Geophys. Geosys.* **2006**, *7*, Q05009. [\[CrossRef\]](#)
40. Paces, J.B.; Miller, J.D., Jr. Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagnetic processes associated with the 1.1 Ga Mid-continent Rift System. *J. Geophys. Res.* **1993**, *98*, 13997–14013. [\[CrossRef\]](#)
41. Ludwig, K.R. *Isoplot: A Plotting and Regression Program for Radiogenic-Isotope Data, Version 3.0*; U.S. Geological Survey Open-File Report; USGS: Reston, VA, USA, 2001; Volume 91–445, 40p.
42. Oldow, J.S.; Bally, A.W.; Ave Lallemand, H.G. Transpression, orogenic float, and lithospheric balance. *Geology* **1990**, *18*, 991–994. [\[CrossRef\]](#)
43. Wright, J.E.; Wooden, J.A. New Sr, Nd, and Pb isotopic data from plutons in the northern Great Basin: Implications for crustal structure and granite petrogenesis in the hinterland of the Sevier thrust belt. *Geology* **1991**, *19*, 4457–4460. [\[CrossRef\]](#)
44. Kalakay, T.J.; John, B.E.; Lageson, D.R. Fault-controlled pluton emplacement in the Sevier fold-and-thrust belt, SW Montana. *J. Struct. Geol.* **2001**, *23*, 1151–1165. [\[CrossRef\]](#)
45. Foster, D.A.; Doughty, P.T.; Kalakay, T.J.; Fanning, C.M.; Coyner, S.; Grice, W.C.; Vogl, J. Kinematics and timing of exhumation of metamorphic core complexes along the Lewis and Clark fault zone, northern Rocky Mountains, USA. In *Exhumation Associated with Continental Strike-Slip Fault Systems*; Till, A.B., Roeske, S.M., Sample, J.C., Foster, D.A., Eds.; Geological Society of America Special Papers; Geological Society of America: Boulder, CO, USA, 2007; Volume 434, pp. 207–232.
46. Elison, M.W.; Speed, R.C.; Kistler, R.W. Geologic and isotopic constraints on the crustal structure of the northern Great Basin. *Geol. Soc. Am. Bull.* **1990**, *102*, 1077–1092. [\[CrossRef\]](#)
47. Foster, D.A.; Fanning, C.M. Geochronology of the northern Idaho batholith and the Bitterroot metamorphic core complex: Magmatism preceding and contemporaneous with extension. *Geol. Soc. Am. Bull.* **1997**, *109*, 379–394. [\[CrossRef\]](#)
48. Miller, E.L.; Gans, P.B. Cretaceous crustal structure and metamorphism in the hinterland of the Sevier thrust belt, western U.S. Cordillera. *Geology* **1989**, *17*, 59–62. [\[CrossRef\]](#)
49. Fleck, R.J. Neodymium, strontium, and trace element evidence of crustal anatexis and magma mixing in the Idaho batholith. In *The Nature and Origin of Cordilleran Magmatism*; Anderson, J.L., Ed.; Geological Society of America Memoir 174; Geological Society of America: Boulder, CO, USA, 1990; pp. 359–373.
50. Gray, K.D.; Isakson, V.; Schwartz, D.; Vervoort, J.D. Orogenic link ~41°N–46°N: Collisional mountain-building and basin closure in the Cordillera of western North America. *Geosphere* **2020**, *16*, 136–181. [\[CrossRef\]](#)
51. Giorgis, S.; Tikoff, B.; McClelland, W. Missing Idaho arc: Transpressional modification of the <sup>87</sup>Sr/ <sup>86</sup>Sr transition on the western edge of the Idaho batholith. *Geology* **2005**, *33*, 469–472. [\[CrossRef\]](#)
52. Hyndman, D.W.; Foster, D.A. The role of tonalites and mafic dikes in the generation of the Idaho batholith. *J. Geol.* **1988**, *96*, 31–46. [\[CrossRef\]](#)
53. Compston, R.R.; Todd, V.R.; Zartman, R.E.; Naeser, C.W. Oligocene and Miocene metamorphism, folding, and low-angle faulting in northwestern Utah. *Geol. Soc. Am. Bull.* **1977**, *88*, 1237–1250. [\[CrossRef\]](#)
54. DuFrane, S.A.; Vervoort, J.D.; Leeman, W.P.; Wolf, D. Hafnium Isotope Composition of Archean Zircons from Xenoliths of the Snake River Plain, Idaho. *Eos Trans. Am. Geophys. Union* **2007**, *88*, V43B-1375.
55. Henstock, T.; Levander, A.; Snelson, C.; Keller, R.; Miller, K.; Harder, S.; Gorman, A.R.; Clowes, R.M.; Burianyk, M.J.A.; Humphreys, E.D. Probing the Archean and Proterozoic lithosphere of western North America. *GSA Today* **1998**, *8*, 16–17.
56. Dueker, K.; Yuan, H.; Zurek, B. Thick-structured Proterozoic lithosphere of the Rocky Mountain Region. *GSA Today* **2001**, *11*, 109. [\[CrossRef\]](#)
57. Manea, V.C.; Manea, M.; Leeman, W.P.; Schutt, D.L. The influence of plume head-lithosphere interaction on magmatism associated with the Yellowstone hotspot track. *J. Volcanol. Geotherm. Res.* **2009**, *188*, 68–85. [\[CrossRef\]](#)
58. Klöcking, M.; White, N.J.; MacLennan, J.; McKenzie, D.; Fitton, J.G. Quantitative relationships between basalt geochemistry, shear wave velocity, and asthenospheric temperature beneath western North America. *Geochim. Geophys. Geosys.* **2018**, *19*, 3376–3404. [\[CrossRef\]](#)
59. Leeman, W.P.; Annen, C.; Dufek, J. Snake River Plain—Yellowstone volcanism: Implications for magma genesis and magma fluxes. *Geol. Soc. Lond. Spec. Pub.* **2007**, *304*, 235–259. [\[CrossRef\]](#)
60. Lum, C.C.L.; Leeman, W.P.; Foland, K.A.; Kargel, J.A.; Fitton, J.G. Isotopic variations in continental basaltic lavas as indicators of mantle heterogeneity: Examples from the western U.S. Cordillera. *J. Geophys. Res.* **1989**, *94*, 7871–7884. [\[CrossRef\]](#)
61. Leeman, W.P.; Schutt, D.L.; Hughes, S.S. Thermal structure beneath the Snake River Plain: Implications for the Yellowstone hotspot. *J. Volcanol. Geotherm. Res.* **2009**, *188*, 57–67. [\[CrossRef\]](#)
62. Harry, D.L.; Leeman, W.P. Partial melting of melt metasomatized subcontinental mantle and the magma source potential of the lower lithosphere. *J. Geophys. Res.* **1995**, *100*, 10255–10269. [\[CrossRef\]](#)

63. McCurry, M.; Rodgers, D.W. Mass transfer along the Yellowstone hot spot track I: Petrologic constraints on the volume of mantle-derived magma. *J. Volcanol. Geotherm. Res.* **2009**, *188*, 86–98. [[CrossRef](#)]
64. Rodgers, D.W.; McCurry, M. Mass transfer along the Yellowstone hot spot track II: Kinematic constraints on the volume of mantle-derived magma. *J. Volcanol. Geotherm. Res.* **2009**, *188*, 99–107. [[CrossRef](#)]

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