1995

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Source of the Northeastern Idaho Batholith: Isotopic Evidence for a Paleoproterozoic Terrane in the Northwestern U.S.[1]

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ABSTRACT

The northeastern portion of the Idaho batholith (NIB) intruded Proterozoic rocks of the Belt-Purcell supergroup between 50 and 90 Ma. Whole-rock Sm-Nd isotopic analyses of batholithic rocks yield depleted mantle model ages (T_{DM}) between 1.72 and 1.93 Ga and values of ϵ_{Nd} between −17.7 and −21.2, similar to associated metamorphic rocks and within the range for Belt-Purcell sedimentary rocks. Premagmatic zircons from one sample of the NIB were analyzed individually using the SHRIMP ion microprobe and yielded a single age population at 1.74 Ga. This apparently single-aged source contrasts with the range of ages reported for zircons from sedimentary rocks of the Belt-Purcell supergroup and suggests that the batholith was not the product of melting Belt-Purcell sediments, nor was it significantly contaminated with these sediments. The source of the batholith, however, appears to be of appropriate age and composition to be a major contributor of sediment to the Belt basin. In addition, the near coincidence of T_{DM} and the age derived from premagmatic zircons in one sample suggests the source of at least part of the batholith was extracted largely from 1.74 Ga depleted mantle, with little or no input from older rocks. If so, this crust may represent a possible continuation of crust of similar age and character exposed to the north in the Canadian cordillera and to the south in Nevada, Arizona, and southeastern California.

Introduction

Crustal and lithospheric age provinces in the western U.S. have been proposed on the basis of the Rb-Sr, Sm-Nd, and U-Pb systematics of Mesozoic and younger igneous rocks (e.g., Doe and Zartman 1979; Zartman 1974; Farmer and DePaolo 1983, 1984; Bennett and DePaolo 1987). In the southwestern U.S., general agreement exists with regard to the location and chronologic characterization (Proterozoic) of most provinces based on both U-Pb and Sm-Nd systematics (e.g., Bennett and DePaolo 1987; Wooden and Miller 1990; Karlstrom and Bowring 1993; Wright and Snoke 1993). In the northwestern U.S., however, this is not the case for two reasons. The first is that Mesozoic terrane accretion and thick accumulations of Neoproterozoic (Belt-Purcell) and younger rocks largely preclude direct observation of underlying basement. The second is that Archean crust and lithosphere may occur throughout the region (e.g., Church 1985; Carlson 1984; Leeman et al. 1985; Lush et al. 1988; Whitehouse et al. 1992; Wright and Snoke 1993). Consequently, the many Proterozoic (~1.5 to 1.8 Ga) Sm-Nd model ages reported for Mesozoic and younger, crustally derived igneous rocks in the region (e.g., Farmer and DePaolo 1983, 1984; Fleck 1990; Norman and Leeman 1989; Fleck and Gunn 1991; Leeman et al. 1991) may result either from the melting of Proterozoic lithosphere or from the mixing of Mesozoic and younger, relatively juvenile material with material derived from Archean sources.

Geologic Setting

The portion of western North America depicted in figure 1 contains a wide variety of tectonically juxtaposed geologic terranes ranging in age from at least middle Archean (>3.0 Ga) to Cenozoic (e.g., Hamilton 1978; Mogk et al. 1992). Initial attempts

[1] Manuscript received June 6, 1994; accepted October 4, 1994.

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[The Journal of Geology, 1995, volume 103, p. 63–72] © 1995 by The University of Chicago. All rights reserved. 0022-1376/95/10301-0010$1.00

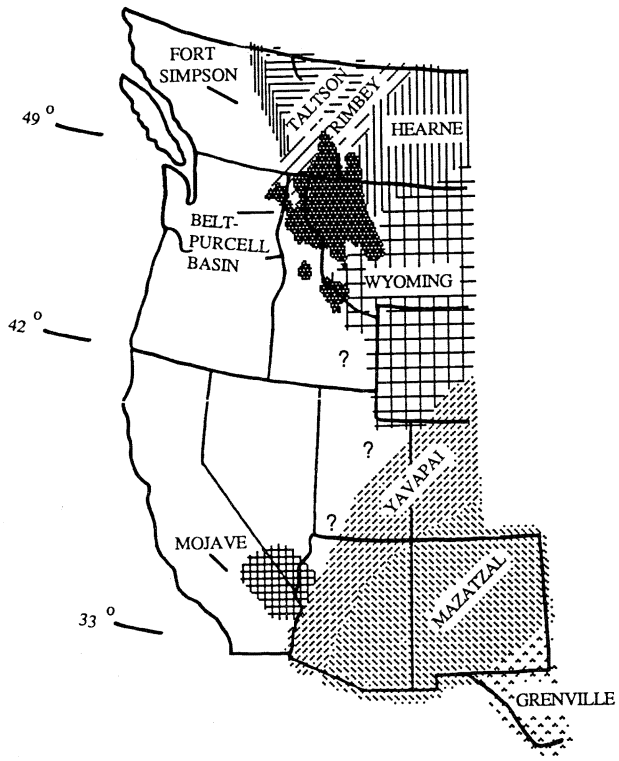

Figure 1. Generalized geologic map of the Precambrian basement provinces of selected parts of western North America. Ages of provinces are: Grenville: 1.0 to 1.2 Ga; Mazatzal: 1.65 to 1.8 Ga; Yavapai: 1.7 to 1.8 Ga; Fort Simpson: 1.84 to 1.86 Ga; Taltson: 1.9 to 2.4 Ga; Mojave: 2.0 to 2.2 Ga; Hearne and Wyoming: >2.6 Ga. Map is drawn after Ross et al. (1992), Hoffman (1989), Karlstrom and Bowring (1993), and Wooden and Miller (1990).

to identify age-coherent crustal segments resulted in the recognition of Pb-isotope provinces by Zartman (1974) and delineation of the "0.706 line" for Sr isotopes as the western limit of Precambrian North America (e.g., Armstrong et al. 1977). The western limit of coherent, exposed Archean crust, however, is found in the northwesternmost Wyoming province and consists of a complex assemblage of middle to late Archean gneissic and metasupracrustal rocks (Mogk et al. 1992; Mueller et al. 1993). To the west of these exposures, Archean crust has been identified as outcrops in northern Nevada (Lush et al. 1988; Wright and Snoke 1993), as crustal xenoliths in Snake River Plain basalts (Leeman et al. 1985), and as a constituent of the crust in northern Washington where Whitehouse et al. (1992) reported Archean $^{207}Pb/^{206}Pb$ ages for zircons from Phanerozoic granitoids. Suggestions for Archean mantle lithosphere west of the Wyoming craton have also been made based on secondary Pb isochrons of Archean age derived from Cenozoic basaltic rocks from the Snake River plain (Leeman 1982), the eastern Cascades (Church 1985), and the Columbia River Plateau (Carlson 1984). In addition, similarities in Sm-Nd and U-Pb systematics between the Wyoming and Mojave provinces have been used to suggest that remnants of the Wyoming craton may extend as far as southeastern California (Bennett and DePaolo 1987; Wooden and Mueller 1991). In aggregate, then, these observations suggest that Archean lithosphere, whether derived from the Wyoming craton or not, is present west of the current western boundary of the Wyoming province and west of traditional estimates of the western boundary of Mesozoic North America.

Paleoproterozoic crust west of the Wyoming craton has been identified only by extrapolation of arrays of discordant zircons from samples of the Idaho batholith and associated metamorphic rocks (e.g., Toth and Stacey 1992; Bickford et al. 1981). Mesoproterozoic gneisses (1.4–1.6 Ga), however, have been identified within the Salmon River arch and in northeastern Washington (e.g., Evans and Zartman 1990; Whitehouse et al. 1992).

Despite evidence for both Archean and Paleoproterozoic crust west of the Wyoming craton, the dominant exposed Precambrian rocks are Meso- to Neoproterozoic quartzose sedimentary and metasedimentary rocks of the Belt and Purcell supergroups. These rocks crop out extensively from the western margin of the northern Wyoming province, where they have been thrust over Archean rocks of the craton, to central Idaho, where they are overthrust by younger rocks (Schmidt and Garihan 1986). They have been the subject of numerous sedimentologic and geochemical studies, including the Sm-Nd study of Frost and Winston (1987). These isotopic data were interpreted to support previous proposals (e.g., McMannis 1963) for a local, eastern, Archean provenance (Wyoming craton) for the basal La Hood conglomerate ($T_{DM} \geq$ 2.91 Ga). Younger units (T_{DM} 1.6–2.1 Ga), however, were interpreted to have had very limited or no contribution from Archean rocks. In a separate attempt to constrain the provenance of sediments of the upper portion of the Belt-Purcell supergroup, Ross et al. (1992) analyzed individual detrital zircon (U-Pb) and monazite (U-Pb, Sm-Nd) grains from several formations. Except for two zircons from the Missoula Group that yielded ages of ~2.6 Ga, $^{207}Pb/^{206}Pb$ ages were Proterozoic (1.07–1.86 Ga).

The northeastern Idaho batholith (NIB; figure 2),

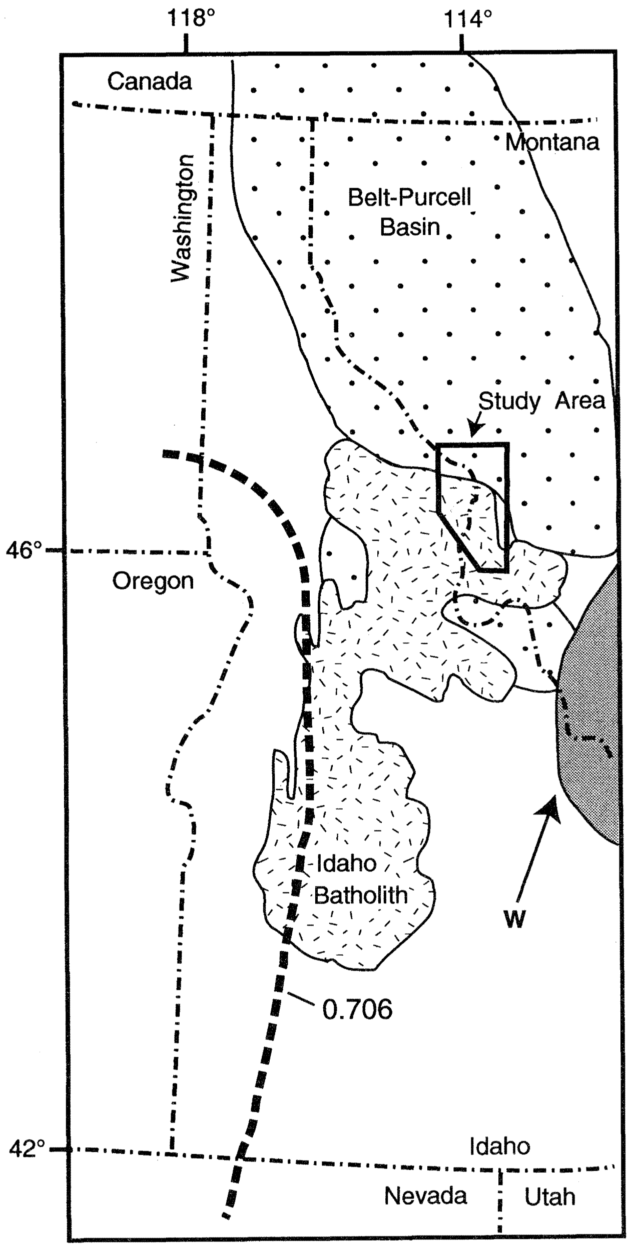

Figure 2. Generalized map of the Idaho batholith and immediate vicinity showing study area and major features discussed in the text: W = western limit of exposed Wyoming craton, 0.706 = $^{87}Sr/^{86}Sr$ value used as indicator of the western limit of cratonic North America in the Mesozoic

also known as the Bitteroot lobe of the Idaho batholith or Bitteroot batholith (Hyndman and Foster 1988), intruded high-grade (including sillimanite zone) rocks of the Belt supergroup about 50 to 90 Ma (e.g., Hyndman 1984; Toth and Stacey 1992). It is composed largely of two-feldspar, two-mica granitoids which range from 65 to 75% SiO_2 and exhibit strongly fractionated REE patterns $(La/Yb)_n$ = ~100). These observations, along with other chemical, petrologic, and field data, have led many workers to attribute its origin to mixing between magmas produced as a result of subduction along the western margin of North America ~50 to ~100 Ma and crustally derived melts (e.g., Shuster and Bickford 1985; Hyndman and Foster 1988). The involvement of crustal rocks is evident in the U-Pb systematics of zircons extracted from many batholithic rocks. These zircons show extreme discordance on U-Pb concordia diagrams. This discordance has been interpreted as the consequence of new overgrowths (50–100 Ma) on older cores (1.5–2.3 Ga) (Chase et al. 1978; Nelson 1981; Bickford et al. 1981; Toth and Stacey 1992; Shuster and Bickford 1985).

Analytical Methods

Samples of both zircons and whole rocks from the Idaho batholith analyzed in this study are splits of those discussed by Shuster and Bickford (1985). Whole-rock chemical (XRF) and isotopic analyses were conducted at the University of Florida according to the methods described in Heatherington and Mueller (1991). Microanalysis of the zircons was undertaken using the ion microprobe SHRIMP. Repeat analyses of the standard Sri Lankan zircon SL13 ($^{206}Pb/^{238}U$ = 0.0928; 572 Ma) during the analytical session were used to determine U, Th, and Pb abundances and to calibrate inter-element isotopic ratios in the unknowns. Pb isotopic ratios were determined directly, with their uncertainties governed by ion-counting statistics. Details of analytical procedures and data reduction for SHRIMP are given by Compston et al. (1984) and Compston and Williams (1992).

The majority of the unknowns yielded very low ^{204}Pb count rates interpreted to indicate very small amounts of non-radiogenic Pb; the isotopic composition of this common Pb is taken to be that of average 100 Ma crustal Pb (approximately the age of the granite) predicted by the model of Cumming and Richards (1975). At these very low observed common Pb contents, however, calculated ages are largely insensitive to the choice of common Pb composition. Ages have been calculated using the decay constants and present-day $^{238}U/^{235}U$ recommended by the IUGS Subcommission on Geochronology (Steiger and Jäger 1977). The discordia regression was done using ISOPLOT (Ludwig 1991). The data, along with further notes on data reduction, are available from *The Journal of Geology* upon request.

Results

Samples of the NIB discussed here (table 1, figure 3) are those of Shuster and Bickford (1985), range from tonalitic to granitic, and are characterized by high silica contents (65–72%) and large ranges in the concentrations of many trace elements, e.g., Sr (300 to 1000 ppm), Ba (700 to 1700 ppm), and Y (1 to 20 ppm). Despite these ranges in elemental abundances, the samples exhibit a limited range of Sm-Nd model ages (1.72 to 1.93 Ga) and ϵ_{Nd} (-17.7 to -21.2) (table 1). These values of ϵ_{Nd} are noticeably more negative than those reported for generally more mafic plutonic rocks from the western margin of the batholith (+8 to -15; Fleck 1990). These differences in ϵ_{Nd} are significant because Nd isotopic compositions are unlikely to be changed by melting and only insignificantly by decay in rocks of this age. Consequently, it seems probable that multiple sources, ranging from crust-like to mantle-like, were involved in generating the various rock compositions present in the Idaho batholith (e.g., Hyndman and Foster 1988; Fleck 1990).

As opposed to isotopic ratios, elemental ratios are likely to be changed during melting and/or fractional crystallization (e.g., Farmer and DePaolo 1983, 1984; Sevigny 1993). In consequence, calculated values such as T_{DM} that require quantitative, unfractionated transfer of Sm and Nd from source to melt to rock are more susceptible to change and are likely to be less reliable tracers of melt heritage. From this perspective, the batholithic samples studied here are not likely to have been derived from any combination of the metamorphic rocks analyzed in this study (xenoliths and screens, table 1) because these rocks have ϵ_{Nd} values (-15.2 to -17.7) slightly higher than those of the batholithic rocks. Both batholithic and metamorphic samples, however, have ϵ_{Nd} values within the overall range of Belt-Purcell sedimentary rocks (-8 to -20; Frost and Winston 1987). Belt-Purcell sedimentary rocks, therefore, cannot be ruled out as potential source material for the batholith on the basis of their Sm-Nd systematics alone.

In addition to Sm-Nd systematics, however, it is also possible to assess the sources of granitoids using the ages of premagmatic or inherited zircons. In the case of the NIB, previously reported upper intercept ages were determined from multigrain zircon samples and generally exhibited severe dis-

Table 1. Selected Data

Sample	IG-10/1	IG-26/2	IG-32A/3	IG-37A/4	ICS-15F/5	IQFG-1Ca/6	IP-7A/7	IGI-17A/8
SiO_2[a]	70.68	65.22	71.28	72.54	63.41	78.43	71.74	69.34
TiO_2	.22	.44	.26	.24	.37	.23	.42	.45
Al_2O_3	15.89	16.66	15.50	14.80	11.69	11.18	14.98	15.97
Fe_2O_3[b]	1.45	3.74	1.88	1.92	4.02	1.19	3.40	3.50
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MgO	.31	.84	.36	.35	6.31	.11	1.74	.92
CaO	2.07	4.31	1.59	1.42	8.45	.44	.53	2.89
Na_2O	4.78	4.66	3.27	3.50	1.74	1.99	2.52	4.71
K_2O	3.50	1.70	5.19	5.30	3.36	3.78	4.00	2.74
P_2O_5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Y[c]	1	20	5	13	36	28	44	15
Zr[c]	149	213	169	173	129	130	174	177
Nb[c]	8	19	20	12	14	11	23	20
Ba[c]	1763	728	1341	889	446	485	768	880
Rb[d]	50	87	146	176	162	105	178	113
Sr[d]	1036	817	355	297	121	144	86	491
Sm[d]	6.6	6.5	4.1	3.6	5.9	4.0	7.0	6.6
Nd[d]	38.0	41.1	28.7	22.7	30.0	18.4	36.2	38.1
$^{87}Sr/^{86}Sr$[e]	.7101	.7094	.7100	.7103	.7639	.7602	.8152	.7168
$^{143}Nd/^{144}Nd$	.51173	.51168	.51161	.51155	.51183	.51186	.51186	.51173
ϵ[e]	-17.7	-18.7	-20.1	-21.2	-15.8	-15.2	-15.2	-17.7
TDM (Ga)	1.84	1.77	1.72	1.93	1.95	2.17	1.88	1.83

Note. n.d. = not determined; b.d. = below detection. Labels are: IG, Idaho batholith; ICS, IQFG, and IP, Idaho batholith country rock; and IGI, Idaho batholith inclusion. The /1, /2, etc., refer to figure 3.
[a] Major elements in weight percent.
[b] Total Fe.
[c] Trace elements by XRF in ppm.
[d] Trace elements by isotope dilution in ppm.
[e] Isotope ratios as measured today.

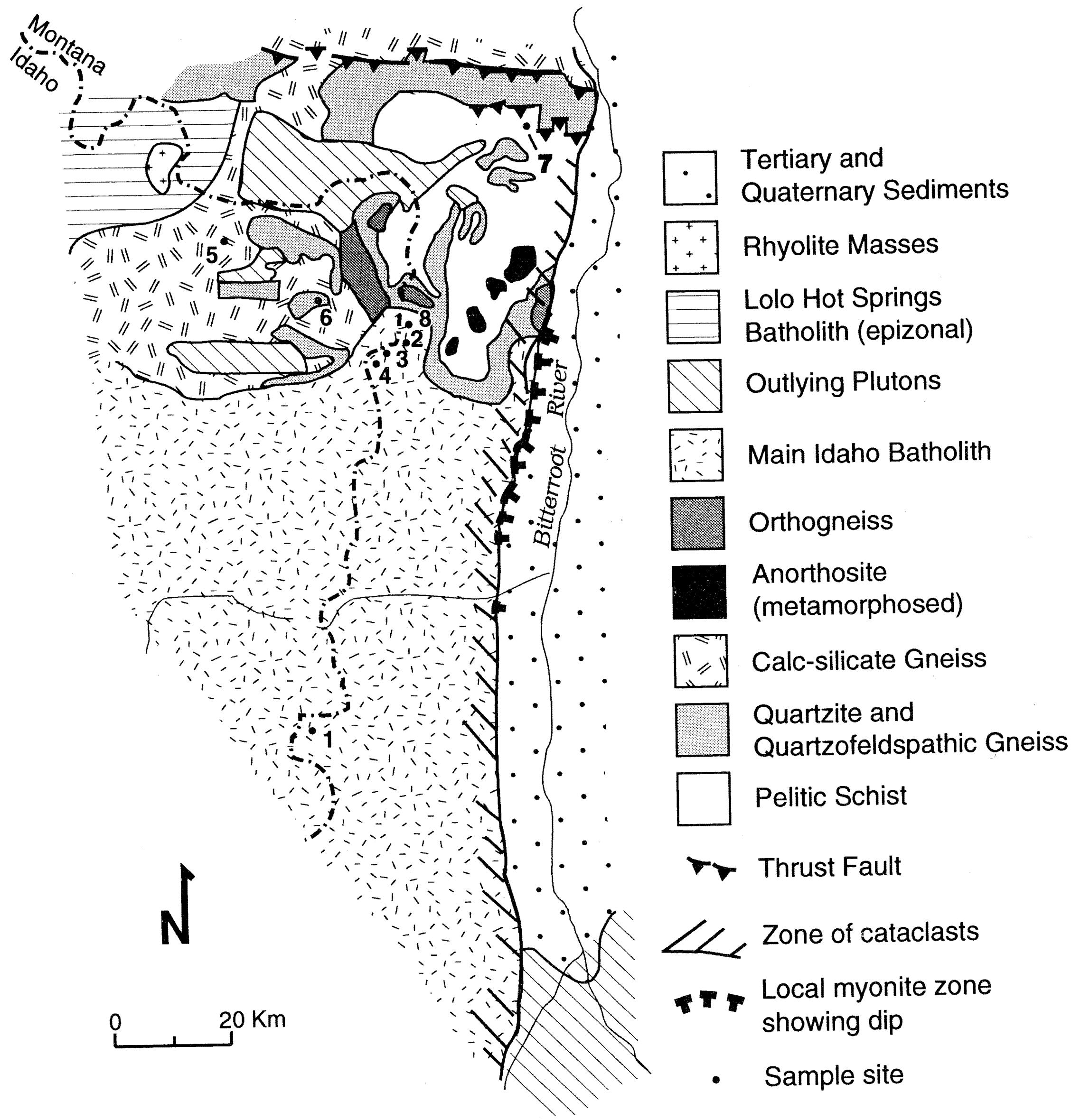

Figure 3. General geologic map (after Chase et al. 1978) of the northeastern border zone of the Idaho batholith showing location of igneous and metamorphic rocks discussed.

cordance (Chase et al. 1978; Nelson 1981; Bickford et al. 1981; Toth and Stacey 1992; Shuster and Bickford 1985). It is consequently not possible to discount the possibility that the range of upper intercept ages is produced by mixing Archean and younger grains, and/or a result of the lengthy extrapolations to concordia.

In order to overcome these potential difficulties, we analyzed the central portions of individual zircons from sample 134.15 of Shuster and Bickford (1985) using the SHRIMP ion microprobe. This resulted in an array of Paleoproterozoic $^{207}Pb/^{206}Pb$ ages. Regression of the associated U-Pb data yielded an upper intercept age of ~1.74 Ga (figure 4), essentially identical to that obtained by conventional multi-grain analyses (Shuster and Bickford 1985). This age is very similar to the 1.75 ± 0.06 Ga concordia intercept age determined for a granitic gneiss within the batholith (Toth and Stacey 1992). Together, these ages suggest that at least the ~1.75 Ga upper intercept ages reported for samples from the NIB are real and indicative of a source of this age. The single age population of premagmatic zircons in this sample and the data of Toth and Stacey (1992), however, contrast with the multi-age character of zircons from Belt sedimentary rocks (Ross et al. 1992). Together with Pb and Sr isotopic data (Shuster 1985; Shuster and Bick-

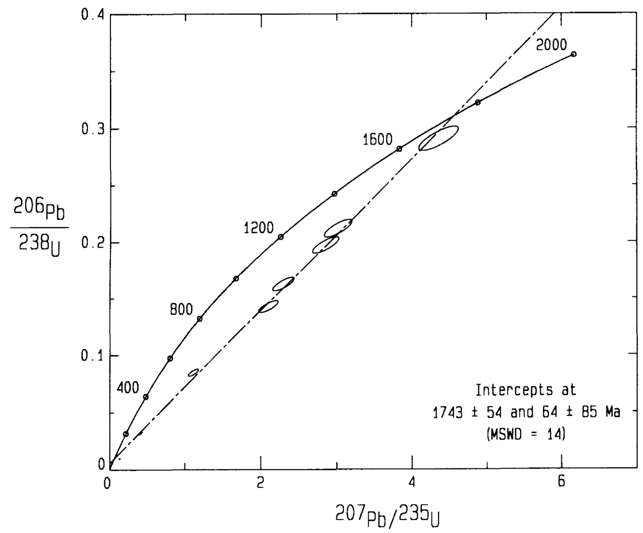

Figure 4. U-Pb concordia plot for cores of individual zircon grains from sample 134.15 of Shuster and Bickford (1985). Regression is via Ludwig (1991). Data were obtained using the SHRIMP ion microprobe and are available from the journal along with additional analytical notes.

ford 1985), this distribution of ages argues against incorporation of rocks of the Belt-Purcell supergroup in the NIB magmas as also suggested by Fleck (1990) based on trace element data.

The exclusion of Belt-Purcell lithologies as a source or significant contaminant of the NIB magmas is important because it allows a more confident assessment of the initial ϵ_{Nd} of the source of the NIB magmas. Calculation of an ϵ_{Nd} for the source at 1.74 Ga yields a value of $\sim +3$, essentially equivalent to the depleted mantle of this age. This calculation involves two assumptions beyond a single-source origin for the NIB magmas, an unchanged Sm/Nd during generation of the NIB magmas, and accuracy of the $^{207}Pb/^{206}Pb$ age derived from the premagmatic zircons. Any change in Sm/Nd during magma genesis would likely have been toward lower values, and lower than true values of Sm/Nd would result in higher estimated initial ϵ_{Nd}s (e.g., a 5% decrease in Sm/Nd yields a change in initial ϵ_{Nd} of $+1$). Conversely, ages younger than the true age would yield lower estimates for initial ϵ_{Nd} (e.g., an 80 m.y. decrease would cause a change in ϵ_{Nd} of -1). This latter possibility must also be considered because the extensive Pb-loss experienced by many of the inherited zircons means that 1.74 Ga should be considered a minimum age. Errors of these magnitudes are not large and, at least on a qualitative basis, tend to counter each other. In consequence, the estimated value of the initial ϵ_{Nd} of the source ($+3$) is probably very close to the true value. If so, it implies that when the source of sample 134.15 formed at $\sim$1.75 Ga, it was derived from the $\sim$1.75 Ga depleted mantle with no significant input from older rocks, including the presently adjacent Wyoming craton. This suggestion is compatible with that of Zartman (1992) who utilized Pb isotopic data from ore leads from the Belt basin to suggest that a relatively juvenile Paleoproterozoic terrane underlay significant portions of the basin. If largely juvenile, as suggested by the Nd and Pb data, this province would be similar in age and composition to many Proterozoic terranes of the southwestern U.S. (e.g., Bennett and DePaolo 1987; Karlstrom and Bowring 1993).

Results of Sr isotopic analyses (table 1) do not form as homogeneous a set of data as do the Sm-Nd values. Initial Sr isotopic values for the NIB range from about 0.706–0.710, generally compatible with a crustal origin. Values for other Late Mesozoic-Early Cenozoic rocks from this area, such as the Boulder batholith and the Pioneer batholith (0.711–0.716, Doe et al. 1968; Arth et al. 1986; Dudas 1991; figure 1), are somewhat higher. The greater mobility of Rb and Sr relative to Sm and Nd in mid- and lower crustal environments is the most likely explanation for the less coherent Rb-Sr data (e.g., Goldstein 1988; table 1).

Discussion

The most critical aspect of the data reported here in terms of characterizing the source of this portion of the NIB is the coherence of the Sm-Nd model ages relative to the age information provided by the U-Pb system in premagmatic zircons. This coherence can be expressed in two ways: (1) the 1.74 Ga age of the premagmatic zircons can be used to calculate a value of ϵ_{Nd} for at least one component of the source of the NIB at 1.74 Ga ($+3$) that is nearly coincident with that of the ϵ_{Nd} value of the model-depleted mantle at 1.74 Ga, or (2) the depleted mantle model age of $\sim$1.7 Ga is generally coincident with the U-Pb concordia intercept age defined by the premagmatic zircons. This concordance of values suggests: (1) at least one of the crustal sources involved in the generation of the NIB formed as part of a relatively juvenile terrane $\sim$1.75 Ga, (2) that the mantle-derived melts that formed that source terrane did not interact with older crust, and (3) that sample 134.15 was probably formed by melting of that source with little interaction with melts derived form 80 Ma depleted mantle or Archean lithosphere. Alternatively, mixing of older (e.g., Archean lithosphere) and younger (e.g., 80 Ma asthenosphere) sources to produce this concordance of zircon and Sm-Nd model ages is possible, but would require three significant, nonchronologically constrained coincidences: (1) mixture of "young" and "old" Nd to yield the present ϵ_{Nd} value of ~ -18, (2) mixture of Sm and Nd abundances to yield a Sm/Nd ratio appropriate to calculate an ~1.75 Ga model age from the observed Nd isotopic composition, and (3) entrainment of 1.74 Ga zircons without including zircons from the source(s) providing the "old" Nd. This set of coincidences seems unlikely.

These data consequently confirm previous suggestions for the presence of ~1.75 Ga crust beneath the NIB (Chase et al. 1978; Nelson 1981; Bickford et al. 1981; Toth and Stacey 1992; Shuster and Bickford 1985). The existence of Paleoproterozoic crust in other parts of the northwestern U.S. has been discussed previously by Sears et al. (1982) who proposed its existence in northern Utah based upon lithostratigraphic correlations with units along the southern boundary of the Wyoming craton. Farmer and DePaolo (1983, 1984) used Sm-Nd systematics on a regional scale to argue for extensive Paleoproterozoic crust in the northern Great Basin and adjoining areas. In addition, Ross et al. (1992) measured U-Pb ages of detrital zircons from three formations of the Belt-Purcell supergroup and found that the majority (17 of 29) gave ages between 1.70 and 1.85 Ga. They used this observation to argue that Paleoproterozoic rocks of the northern Cordillera may have extended south along the western margin of the Wyoming craton during Belt-Windemere time (~0.7–1.3 Ga). In general, these discussions place this Proterozoic terrane west of the present exposures of the Belt and Purcell supergroups, but consider it to have rifted away during the Neoproterozoic (e.g., Sears and Price 1978; Ross and Parrish 1991). This view is consistent with the terrane analyses of Moores (1991) and Hoffman (1989), for example, which do not include a Proterozoic terrane immediately west of the Wyoming craton at present. Despite the general consensus that this terrane was separated from North America in the Neoproterozoic, its present location is not generally agreed upon. For example, initial correlations with the Siberian platform (Sears and Price 1978) appear problematic in light of significant stratigraphic and chronologic discontinuities (e.g., Condie and Rosen 1994). Alternatively, Borg and DePaolo (1994) used Sm-Nd model ages to point out the critical nature of correlations between what they refer to as the Idaho batholith province and the 1.6 to 1.9 Ga provinces in Antarctica and southeastern Australia.

Although it is impossible to say to what extent Paleoproterozoic lithosphere is present west of the Wyoming craton, indirect evidence for its presence is abundant. For example, Paleoproterozoic tectonothermal activity along the western margin of the Wyoming craton is recorded in the form of many Ar-Ar (mica and amphibole) and U-Pb (zircon, sphene, and rutile) mineral ages between 1.6 and 1.8 Ga (e.g., Giletti 1971; O'Neill et al. 1988; Erslev and Sutter 1990; Mueller et al. 1994, unpubl.). This zone of at least partially reset Archean mineral ages is similar to that reported for the southeastern boundary of the province where a Paleoproterozoic arc collided with the Wyoming craton ~1.8 Ga (e.g., Chamberlain et al. 1993). In addition, evidence of ~1.8 Ga mantle activity in this general area has been reported in the form of U-Pb ages of zircons in mantle xenoliths (Rudnick et al. 1993) and inferences drawn from the isotopic systematics of Mesozoic and Cenozoic igneous rocks (e.g., Dudas 1991; Meen and Eggler 1987; O'Brien et al. 1991). Collectively, these data strongly suggest a collisional event along the western margin of the Wyoming craton about 1.6–1.8 Ga.

The presence of ~1.75 Ga crust below the NIB suggests that crust of this age may still underlie much of the area presently overlain by the Belt supergroup (figure 1). This conclusion does not necessarily conflict with the interpretations of Sears and Price (1978), Frost and Winston (1987), or Ross et al. (1992) regarding a more westerly source of zircon and other detritus of Paleoproterozoic age, but supports proposals for the existence of Paleoproterozoic crust east and south of the Belt basin (e.g., Roberts 1986; Sears et al. 1982). The overall extent of this Paleoproterozoic lithosphere is not clear but may represent an extension of similar terranes exposed to the south in Nevada, southeastern California, and throughout the southwestern U.S., and to the north in parts of the Canadian Cordillera (e.g., Wooden and Miller 1990; Karlstrom and Bowring 1993; Ross et al. 1992; Ross and Parrish 1991).

Although Paleoproterozoic lithosphere may extend throughout this region, it is difficult to constrain its degree of continuity. Thomas et al. (1988) interpreted gravity data to indicate a continuous lithospheric province in this region. Gravity data, however, are better suited for recognizing structural provinces than crustal age provinces and geochemical evidence for Archean lithosphere is abundant, as discussed above. The distribution of this lithosphere is undoubtedly the result of the complex history this region, which includes an ~1.75 Ga collisional event, opening of the Belt basin, and late Phanerozoic collisional events (e.g., Erslev and

Sutter 1990; Lucas et al. 1993; Geist et al. 1989; Chamberlain et al. 1993; Leeman et al. 1992). The result of these superposed orogenic events is a chronologically complex lithosphere. Melting of this lithosphere combined with possible interactions with young mantle-derived melts complicates the interpretation of whole-rock isotopic systematics of young igneous rocks and, consequently, the identification of crustal age provinces.

Conclusions

Late Mesozoic to Early Cenozoic silicic igneous rocks of the Bitterroot lobe of the Idaho batholith of the northwestern United States exhibit a limited range of Sm-Nd systematics (ϵ_{Nd} of -18 to -21), premagmatic zircons of ~1.74 Ga, and a wide range of bulk compositions and trace element abundances. The age coherence of premagmatic zircons contrasts with the wide range of ages of detrital zircons reported for Belt-Purcell rocks and suggests the batholith was not derived from melting of Belt-Purcell sedimentary rocks. In addition, the general coincidence at ~1.75 Ga of Sm-Nd depleted mantle model ages calculated for the NIB, the age of a granitic gneiss included within the batholith (Toth and Stacey 1992), and the 1.74 Ga age determined for inherited zircons suggests at least some NIB magmas represent largely uncontaminated melts derived from Paleoproterozoic crust that was itself largely juvenile at the time of its formation. Though the extent of this crust is unknown, it is does not appear to have completely rifted away in the Neoproterozoic and is of appropriate age and composition to have been a major contributor of detritus to the Belt basin. This terrane may be related to its chronologic counterparts exposed in the northern Canadian cordillera and the southwestern United States and, as such, may provide a critical constraint to Neoproterozoic continental reconstructions (Ross and Parrish 1991; Borg and DePaolo 1994).

ACKNOWLEDGMENTS

Supported by grants from NASA (NAG-9-91) and NSF (EAR 8905076) to P. Mueller. W. Compston is thanked for access to SHRIMP. Discussions with D. Mogk, J. O'Neill, and J. Wooden helped clarify our ideas and helpful reviews by Robert Fleck and an anonymous reviewer resulted in an improved manuscript.

REFERENCES CITED

Armstrong, R.; Taubeneck, W.; and Hales, P., 1977, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition, Oregon, Washington, and Idaho: Geol. Soc. America Bull., v. 88, p. 397–411.

Arth, J.; Zen, E.; Sellers, G.; and Hammarstrom, J., 1986, High initial Sr isotopic ratios and evidence for magma mixing in the Pioneer batholith of southwestern Montana: Jour. Geology, v. 94, p. 419–430.

Bennett, V., and DePaolo, D., 1987, Proterozoic crustal history of the western United States as determined by neodymium isotope mapping: Geol. Soc. America Bull., v. 99, p. 674–685.

Bickford, M.; Chase, R.; Nelson, B.; Shuster, R.; and Arruda, E., 1981, U-Pb systematics of zircon cores and overgrowths, and monazite: implications for age and petrogenesis of the northeastern Idaho batholith: Jour. Geology, v. 89, p. 433–457.

Borg, S., and Depaolo, D., 1994, Laurentia, Australia, and Artarctica as a Late Proterozoic supercontinent: constraints from isotopic mapping: Geology, v. 22, p. 307–310.

Carlson, R., 1984, Isotopic constraints on Columbia River flood basalt genesis and the nature of the subcontinental mantle: Geochim. Cosmochim. Acta, v. 48, p. 2357–2372.

Chamberlain, K.; Patel, S.; Frost, R.; and Snyder, G., 1993, Thick-skinned deformation of the Wyoming province during Proterozoic arc-continent collision: Geology, v. 21, p. 995–998.

Chase, R. B.; Bickford, M. E.; and Tripp, S. E., 1978, Rb-Sr and U-Pb isotopic studies of the northeastern Idaho batholith and border zone: Geol. Soc. America Bull., v. 89, p. 1325–1334.

Church, S., 1985, Genetic interpretation of lead-isotopic data from the Columbia River basalt group, Oregon, Washington, and Idaho: Geol. Soc. America Bull., v. 96, p. 676–690.

Compston, W., and Williams, I. S., 1992, Ion probe ages for the British Ordovician and Silurian stratotypes, *in* Webby, X. X., and Laurie, X. X., eds., Global Perspectives on Ordovician Geology: Balkema, Rotterdam, p. 59–67.

———; ———; and Meyer, C., 1984, U-Pb geochronology of zircons from Lunar breccia 73217 using a sensitive high mass-resolution ion microprobe: Jour. Geophys. Res., v. 89 (Supp. B), p. 525–534.

Condie, K., and Rosen, O., 1994, Laurentia-Siberia connection revisited: Geology, v. 22, p. 168–170.

Cumming, G., and Richards, J., 1975, Ore lead isotope ratios in a continuously changing earth: Earth Planet. Sci. Lett.,v. 28, p. 155–171.

DePaolo, D., 1981, Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic: Nature, v. 291, p. 193–196.

Doe, B.; Tilling, R.; Hedge, C.;. and Klepper, M., 1968, Lead and strontium isotope studies of the Boulder batholith, southwestern Montana: Econ. Geol., v. 63, p. 884–906.

———, and Zartman, R. E., 1979, Plumbotectonics, the Phanerozoic *in* Barnes, H. L., ed., Geochemistry of Hydrothermal Ore Deposits: New York, Wiley Interscience, p. 22–70.

Dudas, F., 1991, Geochemistry of igneous rocks from the Crazy Mountains, Montana, and tectonic models for the Montana alkalic province: Jour. Geophys. Res., v. 98 (Supp. B8), p. 13,261–13,277.

Erslev, E., and Sutter, J., 1990, Evidence for Proterozoic mylonitization in the northwestern Wyoming province: Geol. Soc. America Bull., v. 102, p. 1681–1694.

Evans, K., and Zartman, R., 1990, U-Th-Pb and Rb-Sr geochronology of Middle Proterozoic granite and augen gneiss, Salmon River Mountains, east-central Idaho: Geol. Soc. America Bull., v. 102, p. 63–73.

Farmer, G., and DePaolo, D., 1983, Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure, 1, Nd and Sr isotopic studies in the geocline of the northern Great Basin: Jour. Geophys. Res., v. 88, p. 3379–3401.

———, and ———, 1984, Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure 2. Nd and Sr isotopic studies of unmineralized and Cu- and Mo-mineralized granite in the Precambrian craton: Jour. Geophys. Res., v. 89, p. 10,141–10,160.

Fleck, R., 1990, Neodymium, strontium, and trace-element evidence of crustal anatexis and magma mixing in the Idaho batholith: Geol. Soc. America Mem. 174, p. 359–373.

———, and Gunn, S., 1991, The use of integrated geologic, geochemical, and isotopic studies in the identification and interpretation of lithospheric boundaries in the northwestern United States: Geol. Soc. America Abs. with Prog., v. 23, p. A210.

Frost, C. D., and Winston, D., 1987, Nd isotope systematics of coarse- and fine-grained sediments: examples from the Middle Proterozoic Belt-Purcell Supergroup: Jour. Geology, v. 95, p. 309–327.

Geist, D.; Frost, C.; Kolker, A.; and Frost, R., 1989, A geochemical study of magmatism across a major terrane boundary: Sr and Nd isotopes in Proterozoic granitoids of the southern Laramie Range, Wyoming: Jour. Geology, v. 97, p. 331–342.

Giletti, B., 1971, Discordant isotopic ages and excess Argon in biotites: Earth Planet. Sci. Lett., v. 10, p. 157–164.

Goldstein, S., 1988, Decoupled evolution of Nd and Sr isotopes in the continental crust and the mantle: Nature, v. 336, p. 733–738.

Hamilton, W., 1978, Mesozoic tectonics of the western United States in Mesozoic paleogeography of the western United States: Pacific Sect., SEPM Pacific Coast Paleogeog. Sym. 2, p. 33–70.

Heatherington, A., and Mueller, P., 1991, Geochemical evidence for Triassic rifting in southwestern Florida: Tectonophysics, v. 188, p. 291–302.

Hoffman, P., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A., and Palmer, A., eds., The Geology of North America—An overview. (The Geology of North America, Vol. A): Boulder, CO, Geol. Soc. America, p. 447–512.

Hyndman, D. W., 1984, A petrographic and chemical section through the northern Idaho batholith: Jour. Geology, v. 92, p. 83–102.

Karlstrom, K., and Bowring, S., 1993, Proterozoic orogenic history of Arizona, *in* Reed, J., et al., eds., Precambrian: Conterminous U.S. (The Geology of North America, Vol. C-2): Boulder, CO, Geol. Soc. America, p. 188–211.

———, and Houston, R. S., 1984, The Cheyenne belt: analysis of a Proterozoic suture in southern Wyoming: Precamb. Res., v. 25, p. 415–446.

Leeman, W., 1982, Development of the Snake River Plain–Yellowstone Plateau Province: an overview and petrologic model: Idaho Bur. Mines Bull. 26, p. 181–191.

———; Menzies, M.; Matty, D.; and Embree, G., 1985, Strontium, neodymium, and lead isotopic compositions of deep crustal xenoliths from the Snake River Plain: evidence for Archean basement: Earth Planet. Sci. Lett., v. 75, p. 354–368.

———; Norman, M. D.; and Clarke, C. B., 1991, Geochemical evidence for an Archean/Proterozoic terrane boundary north of the Snake River Plain, central Idaho: Geol. Soc. America Abs. with Prog., v. 23, p. A210.

———; Oldow, J. S.; and Hart, W. K., 1992, Lithosphere-scale thrusting in the western U.S. cordillera as constrained by Sr and Nd isotopic transitions in Neogene volcanic rocks: Geology, v. 20, p. 63–66.

Lucas, S.; Green, A.; Hajna, Z.; White, D.; Lewry, J.; Ashton, K.; Weber, W.; and Clowes, R., 1993, Deep seismic profile across a Proterozoic collision zone: surprises at depth: Nature, v. 363, p. 339–342.

Ludwig, K., 1991, ISOPLOT: a plotting and regression program for radiogenic isotope data. U.S. Geol. Survey Open File Rept. 91-445, 38 p.

Lush, A.; McGrew, A.; Snoke, A.; and Wright, J., 1988, Allocthonous Archean basement in the northern East Humboldt Range, Nevada: Geology, v. 16, p. 349–353.

McMannis, W., 1963, La Hood formation—a coarse facies of the Belt Series in southwestern Montana: Geological Society of America Bulletin, v. 74, p. 407–437.

Meen, J., and Eggler, D., 1987, Petrology and geochemistry of the Cretaceous Independence volcanic suite, Absaroka Mountains, Montana, clues to the composition of the sub-Montanan mantle: Geol. Soc. America Bull., v. 98, p. 238–247.

Menzies, M.; Leeman, W.; and Hawkesworth, C., 1983, Isotope geochemistry of Cenzoic volcanic rocks reveals mantle heterogeneity below western USA: Nature, v. 303, p.205–209.

Mogk, D.; Mueller, P.; Wooden, J.; and Bowes, D., 1992, The northern Wyoming Province: contrasts in Archean crustal evolution (USA), *in* Bartholomew, M.; et al., eds., Characterization and Comparison of Ancient (Precambrian-Mesozoic) Continental Margins (Proc. 8th Int. Conf. Basement Tectonics, Butte, MT, 1988): Dordrecht, Kluwer, p. 283–297.

Moores, E., 1991, Southwest U.S.–East Antarctic (SWEAT) connection: a hypothesis: Geology, v. 19, p. 425–528.

Mueller, P. A.; Mogk, D. W.; D'Arcy, K.; Heatherington, A.; Hofle, J.; Murphy, J.; Thurston, P.; and Wooden, J., 1990, Crustal evolution in the Montana metasedimentary terrane, *in* Taylor Colloq. (Origin and Evolution of Planetary Crusts) Abs.; Canberra, Australian Nat. Univ., p. 23.

———; Shuster, R.; Wooden, J.; Erslev, E.; and Bowes, D., 1993, Age and composition of Archean crystalline rocks from the southern Madison Range, Montana: implication for crustal evolution in the Wyoming craton: Geol. Soc. America Bull. v. 105, p. 437–446.

———; Wooden, J.; and Nutman, A. D., 1992, 3.96 Ga zircons from an Archean quartzite, Beartooth Mountains, Montana: Geology, v. 20, p. 327–330.

Nelson, B. K., 1981, U-Pb isotopic systematics in the northeast border zone of the Idaho batholith, Bitterroot Range, Montana: Unpub. M.S. Thesis, University of Kansas, Lawrence, KS, 88 p.

Norman, M., and Leeman, W., 1989, Geochemical evolution of Cenozoic-Cretaceous magmatism and its relation to tectonic setting, southwestern Idaho, USA: Earth Planet. Sci. Lett., v. 94, p. 78–96.

O'Brien, H.; Irving, A.; and McCallum, S., 1991, Eocene potassic magmatism in the Highwood Mountains, Montana: petrology, geochemistry, and tectonic implications: Jour. Geophys. Res., v. 98, B8, p. 13,237–13,260.

O'Neill, J.; Duncan, M.; and Zartman, R., 1988, An Early Proterozoic gneiss dome in the Highland Mountains, southwestern Montana: Montana Bur. Mines Geol. Spec. Pub. 96, p. 81–88.

Roberts, S. editor, 1986, Belt Supergroup, a guide to Proterozoic rocks of western Montana and adjacent areas: Montana Bur. Mines Geol. Spec. Pub. 94, 000 p.

Ross, G., and Parrish, R., 1991, Detrital zircon geochronology of metasedimentary rocks in the southern Ominica Belt, Canadian Cordillera: Can. Jour. Earth Sci., v. 28, p. 1254–1270.

———; ———; and Winston, D., 1992, Provenance and U-Pb geochronology of the Mesoproterozoic Belt Supergroup (northwestern United States): implications for age of deposition and pre-Panthalassa plate reconstructions: Earth Planet. Sci. Lett., v. 113, p. 57–76.

Rudnick, R.; Irving, A.; and Ireland, T., 1993, Evidence for 1.8 Ga mantle metasomatism beneath the northwestern margin of the Wyoming craton from SHRIMP analyses of zircons in ultramatic xenoliths: EOS Supplement, v. 74, no. 16, p. 320.

Sears, J. W.; Graff, P. J.; and Holden, G. S., 1982, Tectonic evolution of lower Proterozoic rocks, Uinta Mountains, Utah and Colorado: Geol. Soc. America Bull. v. 93, p. 990–997.

———, and Price, R. A., 1978, The Siberian connection: a case for Precambrian separation of the North America and Siberian cratons: Geology, v. 6, p. 267–270.

Schmidt, C., and Garihan, J., 1986, Middle Proterozoic and Laramide tectonic activity along the southern margin of the Belt Basin: Montana Bur. Mines Geol. Spec. Pub. 94, p. 217–235.

Shuster, R. D., 1985, Geochemical and isotopic evidence for the petrogenesis of the northeastern Idaho batholith, Bitterroot Range, Montana and Idaho: Unpub. Ph.D. Thesis, University of Kansas, Lawrence, KS, 93 p.

———, and Bickford, M. E., 1985, Chemical and isotopic evidence for the petrogenesis of the northeastern Idaho batholith: Jour. Geology, v. 93, p. 727–742.

Steiger, R., and Jager, E., 1977, Subcommission on geochronology: conventions on the use of decay constants in geochronology and cosmochronology: Earth Planet. Sci. Lett., v. 30, p. 359–362.

Thomas, M.; Grieve, R.; and Sharpton, V., 1988, Gravity domains and assembly of the North American continent by collisional tectonics: Nature, v. 331, p. 333–334.

Toth, M., and Stacey, J., 1992, Constraints on the formation of the Bitterroot lobe of the Idaho batholith, Idaho and Montana, from U-Pb zircon geochronology and feldspar Pb isotopic data: U.S. Geol. Survey Bull. 2008, 14 p.

Whitehouse, M.; Stacey, J.; and Miller, F., 1992, Age and nature of the basement in northeastern Washington and north Idaho: isotopic evidence from Mesozoic and Cenozoic granitoids: Jour. Geology, v. 100, p. 691–701.

Wooden, J., and Miller, D., 1990; Chronologic and isotopic framework for Early Proterozoic crustal evolution in the eastern Mojave desert region, SE California: Jour. Geophys. Res., v. 95, B12, 20, 133-20, 146.

———, and Mueller, P. A., 1988, Pb, Sr, and Nd isotopic composition of Late Archean igneous rocks, eastern Beartooth Mountains: Implications for crust-mantle evolution: Earth and Planetary Science Letters, v. 87, p. 59–72.

———, and ———, 1991, A Pb isotopic paradox for granitoids: low-mu rocks from high-mu sources, *in* Chappell, B.; ed., Second Hutton symposium on granites and related rocks: Bur. Min. Res. Geol. Geophys. Record 1991/25, p. 116.

Wright, J., and Snoke, A., 1993, Tertiary magmatism and mylonitization in the Ruby–East Humbolt metamorphic core complex, northeastern Nevada: U-Pb geochronology and Sr, Nd, and Pb isotope geochemistry: Geol. Soc. America Bull., v. 106, p. 935–952.

Zartman, R. E., 1974, Lead isotope provinces in the Cordillera of the western United States and their geological significance: Econ. Geol., v. 69, p. 792–805.

———, 1992, Archean crustal lead in the Helena Embayment of the Belt Basin, Montana, *in* Bartholomew, M. J., et al., eds., Characterization and Comparison of Ancient Mesozoic Continental Margins (Proc. 8th Int. Conf. Basement Tectonics, Butte, MT, 1988): Dordrecht, Kluwer, p. 699–710.