Relationship of Lithospheric Age and Composition to Mineral Resources Within, Beneath, and Adjacent to the Belt Basin

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Final Technical Report

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Introduction

The objective of this study was to develop a better understanding of the distribution, age, composition, and origin of Precambrian basement along and under the Belt basin in western Montana. This information is critical to evaluating the USGS model for Phanerozoic mineralization in this area, which relates the age and extent of juvenile character of Precambrian basement to the age, origin, and composition of mineralization in the region in and around the Belt basin. The proposal laid out two distinctly different approaches to the problem of characterizing the basement to the Belt basin region.

Results

Part I. The first phase of the project involved collecting and analyzing samples of exposed basement within thrust slices along the exposed western margin of the Wyoming Province. Basement samples from the following locations were collected, and zircons from a selected suite were analyzed for crystallization and/or metamorphic ages.

Samples	SHRIMP U-Pb zircon ages

Armstead anticline: Two samples of what proved to be metasedimentary rocks from outcrops immediately north of Clark Canyon Reservoir [N44°59.922’ W112°53.943] yielded a range of U-Pb ages for detrital zircons from 2100 to 2700 Ma. This confirms the Proterozoic age of these rocks, but does not provide any information on magmatic events.

Biltmore anticline: An orthogneiss collected from basement exposures in the anticline [N45˚28.735' W112˚28.449'] yielded a U-Pb crystallization age of 1892±20 Ma.

Pioneer Mountains: An orthogneiss present as a large pendant in the Pioneer batholith [N45˚40.217' W112˚57.153'] yielded a U-Pb crystallization age of 1863±13 Ma.

Beaverhead Range: A sample of hornblende-bearing orthogneiss from Medicine Lodge Creek drainage in the Beaverhead uplift [N44°43.669’ W113°2.157’] yielded a crystallization age of ~2450 Ma with a strong metamorphic overprint that resulted in new zircon growth at ~1780 Ma.

These data contradict assumptions by numerous, earlier workers that basement exposed west of the Wyoming province (i.e., Ruby and Highland Ranges) is Archean in age. These data show clearly that the basement exposed in thrust slices and roof pendants west of the Highland Range is universally Proterozoic in age. Absolute ages for crystallization of magmatic rocks varies considerably, from ~1.8 to almost 2.5 Ga, and appear to represent a previously undefined age province, the Selway terrane (Foster et al, 2006a). Additional geochemical studies of these rocks should place better constraints on their origin, but their limited exposure make it unlikely that their spatial relationships can be further constrained by direct observation.

Part II. The second phase of the project included collecting samples of Phanerozoic plutonic rocks, and analysis of their geochemical and isotopic compositions to infer the age of the underlying basement, specifically the lower crust. This project funded the masters thesis research of Kelly Probst at the University of Florida. Kelly is in the final stages of writing up the results of her thesis project and this will be submitted to Northwestern Geology in April 2007. The attached tables (Tables 1 and 2) include the samples collected, their locations, mineralogy, elemental abundances and their isotopic compositions. In short, these data strongly suggest that Archean crust does exist within the Great Falls tectonic zone between the Little Belt Mountains and the Idaho batholith.

Nature of the basement to the Belt basin

The overarching goal of this project was to further our understanding of the age, origin, and distribution of Precambrian basement in and around the Belt basin. Towards that end we have developed the map of crustal age provinces shown in Figure 1. The distribution depicted in Figure 1 is based on direct measurements from exposures of mainly Archean rocks from the Wyoming craton (e.g., Mogk et al. 1992; Chamberlain et al. 2003), Paleoproterozoic and less abundant Archean rocks in the Great Falls tectonic zone (e.g., Mueller et al. 2002, 2004a; Kellogg et al. 2004; Vogl et al. 2002, 2003, 2004a,b; Foster et al. 2006a), along with evidence for 2.4-1.6 Ga basement beneath the Belt basin (this study), and the Idaho batholith (e.g., Mueller et al. 1995, 2004a; Foster and Fanning, 1997; Foster et al. 2002, 2006a; Sims et al. 2004, 2005). Salient geochemical, petrologic, and structural aspects of the provinces relative to the origin and configuration of the basement are summarized below.

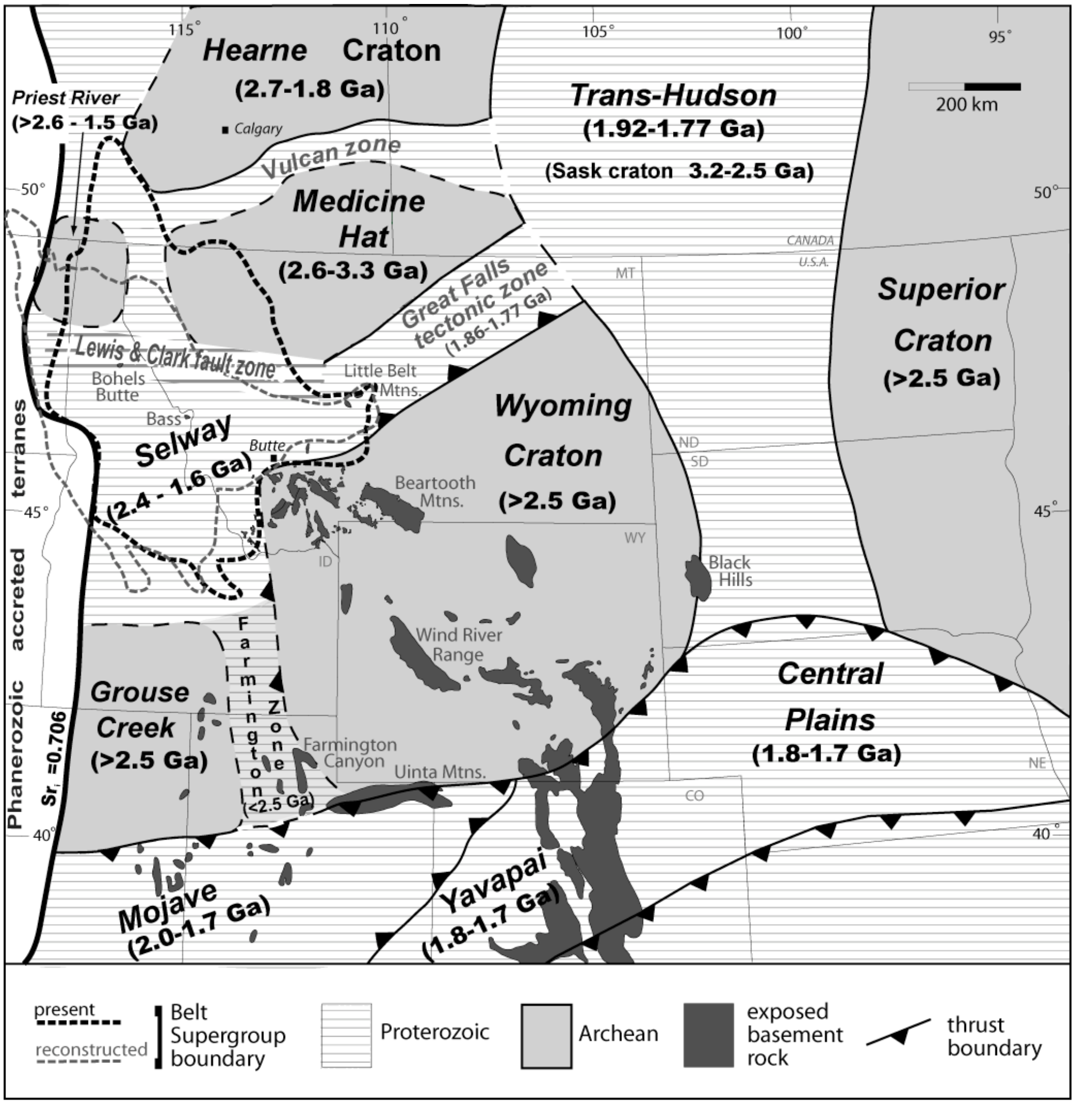

Figure 1. Map of basement provinces of SW Laurentia (after Ross et al.1991; Condie 1992; Karlstrom et al. 2002; Foster et al. 2006a). The outline of the Belt Supergroup is shown in the present location and the reconstructed location based on Price and Sears (2000).

Wyoming Province

The Wyoming province is a geophysically and geochemically distinct Archean craton that contains a unique assemblage of primarily Late Archean rocks (e.g., Wooden and Mueller 1988; Wooden et al. 1988; Dutch and Nielson 1990; Mogk et al. 1992; Frost et al. 1998; Henstock et al. 1998; Chamberlain et al. 2003). The lithosphere of the Wyoming province is unusually thick and strong, and has a distinctive velocity structure that readily distinguishes it from adjacent younger lithosphere (e.g., Thomas et al. 1987; Henstock et al. 1998; Dueker et al. 2001). The northwesternmost part of the Wyoming province consists of a distinct subdivision known as the Montana metasedimentary terrane. This terrane is dominated by middle Archean gneisses (3.2-3.5 Ga; e.g., Mueller et al. 1993; Mueller et al., 2004b) intercalated with metasedimentary rocks (Peale 1896). Crust of the Montana metasedimentary terrane is geochemically distinct from the crust of other parts of the Wyoming province as well as the Superior province and other Archean terranes within Laurentia and globally (e.g., Wooden and Mueller 1988; Mueller and Wooden 1988; Zartman 1992; Frost et al. 1998). Rock ages from 2.5 to 3.5 Ga, detrital zircon and Sm-Nd model ages to 4.0 Ga, and uniquely enriched Pb isotopic signatures provide significant age/isotopic contrasts compared to adjacent, younger terranes (e.g., Mueller and Wooden 1988; Frost 1993). To the south, TTG suite rocks of the Beartooth-Bighorn magmatic zone (~2.9 Ga) and the Wyoming greenstone terrane (2.5-2.8 Ga) constitute the western boundary of the Wyoming craton (Mogk et al. 1992; Chamberlain et al. 2003).

Medicine Hat Block

The Medicine Hat block of northwestern Montana and southern Alberta (Ross et al. 1991; Villeneuve et al. 1993; Lemieux et al. 2000) is another Archean terrane known only from borehole intersections and geophysical data. This Archean block may be the southernmost part of the Hearne Province (Hoffman 1989), but has also been proposed to be part of the Wyoming province based on seismic studies (e.g., Henstock et al. 1998). The western extent of the Medicine Hat block is poorly defined. It may continue west into northwestern Washington and northern Idaho where Archean rocks are exposed in the Priest River complex (Evans and Fischer 1986; Doughty et al. 1997) and inferred by isotopic tracer data and xenocrystic zircons from Eocene plutons (Whitehouse et al. 1992). It may, however, extend only as far west as the eastern part of the Mesoproterozoic Belt basin. Sims et al. (2004) separate the Medicine Hat block from the basement in the Priest River complex, based on magnetic anomalies. The southeastern border of the Medicine Hat Block in central Montana is the Great Falls tectonic zone (O'Neill and Lopez 1985; O'Neill 1998) and it is bounded on the east by the Trans-Hudson orogen. The southwestern border may lie along the trace of the Lewis and Clark fault zone (Foster et al. 2006a,b).

The Lewis and Clark fault zone is a complex, long-lived series of strike-slip and oblique slip faults that predate the Mesoproterozoic Belt basin and extend from northeastern Washington through central Montana (e.g., Reynolds 1979). The fault zone formed a major boundary between depocenters in the central Belt basin and the northern margin of the eastern Belt basin (Harrison et al. 1974; Winston 1986; Reynolds 1979). The fault zone was reactivated during Cretaceous to Paleogene thrusting (Sears et al. 2000) and served as a major transfer structure for Eocene extension (Reynolds 1979; Doughty and Sheriff 1992; Foster et al. 2006b). Proterozoic anorthosite exposed along the southern side of the Lewis and Clark zone in the Bohels Butte block in the Clearwater metamorphic core complex gives a U-Pb zircon crystallization age of ~1.79 Ga (Doughty and Chamberlain, pers. com. 2005).

Grouse Creek block

We propose the name Grouse Creek block to include Archean rocks (*ca.* 2.5-2.6 Ga) that occur west of the present western limit of semi-continuous exposures of the Wyoming craton. Archean rocks crop out in the Grouse Creek Range, Albion Range, and the East Humbolt Range, where they are strongly reworked by Paleoproterozoic and Phanerozoic events (e.g., Armstrong and Hills 1967; Wright and Snoke 1993; Egger et al. 2003;

Premo et al. 2005). The deep crust beneath the central Snake River Plain is Archean based on Pb and Nd isotope data of Cenozoic lavas and xenoliths, and zircons in metaigneous xenoliths with ages centered on 2.6 – 3.2 Ga (Leeman et al. 1985; Wolf et al. 2005). Isotopic signatures from Cretaceous igneous rocks also suggest that >2.5 Ga crust exists south of the Snake River Plain (Fleck and Wooden 1997). Exposures of Archean rocks in the northern Great Basin and inferred Archean crust beneath the Snake River Plain are apparently separated from the contiguous Archean of the Wyoming Craton by Paleoproterozoic rocks (2.45-1.6 Ga) exposed in the Wasatch Range (e.g., Farmington Canyon complex, Bryant 1988; Nelson et al. 2002; Mueller et al. 2004a), which is why we define it as a separate block. The southern margin of the Grouse Creek block may be located between the East Humbolt Range and the Ruby Mountains in Nevada (Wright and Snoke 1993; Premo et al. 2005), which puts it near the westward trend of the Cheyenne Belt (Karlstrom and Houston 1984). The northern margin is probably near the northern edge of the Snake River plain. This block may or may not extend west to the Neoproterozoic rifted margin.

It is currently unclear if the Grouse Creek block is completely separated from the Wyoming craton in the deep crust. It is possible that the metasedimenary rocks in the Farmington Canyon complex, which comprise Archean and earliest Paleoproterozoic detritus, were deposited within a late Archean-earliest Paleoproterozoic rift within Wyoming, or along the late Archean passive margin of Wyoming. Orogeny and magmatism in the Farmington complex at ~2.45 Ga and ~1.8 Ga (Barnett et al., 1993; Nelson et al., 2002; Mueller et al. 2004a) suggests accretion of Grouse Creek occurred in Paleoproterozoic time. The Grouse Creek block could, therefore, be an accreted Archean block, a rifted fragment of Wyoming that re-accreted, or part of Wyoming separated by a younger intracratonic rift/mobile belt. The area between the known Archean in the Wyoming craton and the Grouse Creek block is referred to here as the Farmington zone.

Great Falls tectonic zone

Proterozoic reactivation of Archean rocks of the northwestern Wyoming Craton was first recognized by Hayden and Werhenberg (1959), who reported Paleoproterozoic K-Ar mineral ages from Archean gneisses. O'Neill and Lopez (1985) used these mineral ages and other thermochronologic data (e.g., Giletti 1966), along with geophysical and structural trends in younger rocks, to propose the existence of the Great Falls tectonic zone. They speculated that the Great Falls tectonic zone marks the Paleoproterozoic collision between the Archean Wyoming and Hearne/Medicine Hat provinces.

Geophysical studies have suggested the presence of a north-dipping paleo-subducted slab beneath the Medicine Hat/Hearne block that may be related to the collision that led to the development of the Great Falls tectonic zone (Gorman et al. 2002; Ross 2002). Although the age of this slab cannot be specified, Mueller et al. (2002) have shown that Precambrian rocks in the Little Belt Mountains are dominated by 1.86 Ga calc-alkaline metaigneous rocks that exhibit trace element and Nd isotopic signatures suggestive of petrogenesis in a convergent environment in which juvenile lithosphere was consumed. These data suggest that the slab is likely to be Proterozoic and that oceanic lithosphere was being subducted beneath the Medicine Hat block at ca. 1.86 Ga. We refer to this calc-alkaline assemblage as the Little Belt arc (Volg et al. 2004a; Foster et al. 2006a).

The western Great Falls tectonic zone appears to have had a distinctly different tectonothermal history than the part exposed in the Little Belt Mountains (Giletti 1966; Harlan 1996; Roberts et al. 2002; Brady et al. 2004; Mueller et al. 2004b, 2005). U-Pb data from zircon and monazite demonstrate that the Archean gneisses in the Tobacco Root and Highland Mountains experienced granulite facies metamorphism and partial melting ca. 1.77 Ga ago (Cheney et al. 2004; Mueller et al. 2004b, 2005). This is nearly 100 Ma later than the peak of magmatism and metamorphism in the exposed rocks of the Little Belt arc.

Holm and Schneider (2002) and Vogl et al. (2004a) reported $^{40}Ar/^{39}Ar$ ages for biotite and amphibole from the Little Belt Mountains that suggest rapid cooling through the biotite closure temperature (~350-300˚C) by ~1.75-1.71 Ga. K-Ar and $^{40}Ar/^{39}Ar$ data from the western Great Falls tectonic zone, where Archean rocks are overprinted, scatter considerably (~1.6-1.9 Ga; summary in Brady et al. 2004), and in some cases exceed U-Pb zircon and monazite ages. These apparent ages may reflect a single event with variable cooling histories, more than one event (+/- variable cooling histories), or a complex combination of cooling ages and variable excess argon contamination. It is unclear, therefore, whether the deformation and heating recorded in the central and western Great Falls tectonic zone reflect a single collisional event (i.e., Wyoming-Medicine Hat) or two distinct events.

The northwestern border of the Wyoming craton, therefore, lies along the 1.86-1.77 Ga Great Falls tectonic zone. The western border must be between the exposed Archean in SW Montana and western Wyoming and the Idaho batholith, which is underlain by mostly Paleoproterozoic crust (Mueller et al. 1995; Foster and Fanning 1997). Boundaries between these basement provinces are obscured by the Belt Supergroup, Phanerozoic strata, Idaho batholith, and other Cretaceous-Eocene igneous rocks.

Selway terrane

We have proposed the term Selway terrane for the region underlain by Paleoproterozoic (1.6-2.4 Ga) metamorphic and igneous rocks west of the largely Archean rocks in the basement-cored, Laramide uplifts of SW Montana. These Paleoproterozoic rocks crop out in the Pioneer Range, Biltmore anticline, Tendoy Range, Highland Range, Beaverhead Range, Bitterroot Range, and at Bohels Butte (e.g., this study; O'Neill et al. 1988; Zen 1988; Toth and Stacey 1992; Ruppel et al. 1993; Foster et al. 2002; Kellogg et al. 2003; Mueller et al. 2004a, 2005; Doughty and Chamberlain in press; Foster et al. 2006a). Archean rocks have not been documented in any of these areas except the Highland Mountains (O'Neill et al. 1988). The outcrops are all within the Sevier fold and thrust belt and most occur at the tops of major footwall ramps near the eastern part of the thrust belt (Sears et al. 1988; Kalakay et al. 2001). This is consistent with the interpretation that the western edge of the thick Wyoming craton is within this area. Magnetic anomaly patterns also suggest the presence of a major basement boundary along the edge of the thrust belt (Sims et al. 2004).

U-Pb zircon crystallization ages of the basement rocks west of the large Archean-cored, Laramide basement uplifts in SW Montana, along with secondary isotope systematics and isotopic evidence and xenocrystic zircons from Cretaceous and Tertiary granitoids, including the northern Idaho batholith (Bitterroot lobe), Pioneer batholith, Boulder batholith, Tobacco Root batholith, and Mount Powell batholith suggest that the crust west of exposed Archean crust in SW Montana is largely Paleoproterozoic in age (Doe et al. 1968; Bickford et al. 1981; Schuster and Bickford 1985; Toth and Stacey 1992; Fleck 1990; Mueller et al. 1995, 1996; Foster and Fanning 1997; O'Neill 1998; Foster et al. 2001; Lund et al. 2002; Murphy et al. 2002; Foster et al. 2006a; this study).

Most of the Idaho batholith intruded Precambrian continental crust, with only the western margin developed over Phanerozoic accreted terranes (Armstrong et al. 1977; Hamilton 1978; Hyndman 1983; Fleck and Chris 1985; Lund and Snee 1988). Initial $^{87}Sr/^{86}Sr$ ratios of northern Idaho batholith plutons generally increase from values of ~0.704 in the western border quartz diorites and tonalites to >0.706 to 0.712 in the "main-phase" (Armstrong et al. 1977; Fleck and Chris 1985). Epsilon Nd values from the western border zone plutons range from +2 to +6, and from the "main phase" plutons range from -17.7 to -21.2 (Fleck 1990; Mueller et al. 1995). The Sm-Nd data from the main phase plutons give depleted mantle model ages of 1.72-1.93 Ga (Mueller et al. 1995). U-Pb ages of inherited zircons in the main phase granitoids dominantly range from 1.5-2.3 Ga (Bickford et al. 1981; Shuster and Bickford 1985; Toth and Stacey 1992; Mueller et al. 1995; Foster and Fanning 1997; Foster et al. 2001). SHRIMP ion probe results from single grains of inherited zircon in the northern Idaho batholith (Idaho-Bitterroot batholith) give ages ranging from 0.7 to 2.5 Ga, but several samples give single age populations and concordant grains of 1.74-1.75 Ga (Mueller et al. 1995; Foster and Fanning 1997). These data, combined with the similar Nd depleted mantle model age for these individual samples, suggest that a significant portion of the crust beneath the Idaho-Bitterroot batholith is made up of relatively juvenile ~1.75 Ga material (Mueller et al. 1995; Foster and Fanning 1997). Pb-isotopic data from the central Idaho-Bitterroot batholith also indicate a primitive, arc-like source with an age of 1.6-1.8 Ga (Toth and Stacey 1992).

Initial Sr isotopic values for the Late Cretaceous Pioneer batholith range from 0.7110 to 0.7160 (Arth et al. 1986; Mueller et al. 1997), and Pb isotopes give a model age of 1.9±0.2 Ga (Doe et al. 1968; Zen 1992). These results suggest involvement of mainly Paleoproterozoic crust, as do inherited zircon ages of ~1.4 and 1.7-1.8 Ga for the Grayling Lake granite and Uphill Creek granodiorite reported by Murphy et al. (2002).

Initial Sr isotopic ratios for the Late Cretaceous Boulder batholith, including the Butte quartz monzonite, Marysville stock, and Hell Creek pluton range from 0.7055 to 0.7092, and are significantly lower than values for the Pioneer batholith (Doe et al. 1968; Mueller et al. 1997). A Proterozoic Pb isotopic model age for the Boulder batholith (2.1 ± 0.3 Ga) is similar to that of the Pioneer plutons (Zen 1992). Inherited zircons from several granitic intrusions in the Boulder batholith give abundant *ca.* 1.86-2.4 Ga ages, with the exception of the Radar Creek pluton, which intrudes Archean rocks and contains Archean inherited zircon (Mueller et al. 1997; Lund et al. 2002).

The ~75 Ma Tobacco Root batholith also intrudes exposed Archean rocks (Mueller et al. 1996; Vitaliano et al. 1980). The Tobacco Root batholith has epsilon Nd values ranging from -18.9 to -19.1, and Sm-Nd depleted mantle model ages of 1.63-1.90 Ga (Mueller et al. 1996). Inherited zircons in the Tobacco Root batholith range in age from 2.2-3.0 Ga, generally consistent with the Archean country rocks. These results suggest derivation from Archean and Proterozoic crustal sources along with a volumetrically significant mantle-derived component that resulted in the relatively low initial Sr value of 0.7057-0.7067 for this pluton. These data from the Tobacco Root batholith suggest that some tectonic or magmatic layering of Archean and Proterozoic crust is present along the edge of the Wyoming craton.

In summary, the inherited zircon data from the Boulder batholith and Pioneer batholith suggest the involvement of crust of similar age to that exposed in the central Great Falls tectonic zone in the Little Belt (Mueller et al. 2002) and Pioneer Mountains (Foster et al. 2006a). The sources of the Idaho batholith are somewhat more varied, but show a major component of the crust beneath it formed at about 1.73-1.75 Ga, or about 100 Ma younger than most of the crust in the central Great Falls tectonic zone.

The variation in U-Pb zircon ages for the basement exposures in the Selway terrane indicate Proterozoic rock-forming events ranging in age from about 2.45 Ga (Kellogg et al. 2003; Mueller et al. 2004a) to about 1.8 Ga (Foster et al. 2006a). Isotopic tracer data and inherited zircons from the Cretaceous plutons indicate that Proterozoic lower crust west of this area includes rock-forming events of ca. 1.8-1.6 Ga. High-grade metamorphism and partial melting associated with orogenic events that overprint Archean rocks in the NW Wyoming craton (e.g., Tobacco Root and Highland Mountains), indicate orogenic events between ~2.4 and ~1.77 Ga (Mueller et al. 1994, 2004a,b, 2005; Roberts et al. 2002; Sims et al. 2004). Because of the limited and discontinuous exposure of the Paleoproterozoic rocks and the currently limited geochronologic data, it is not possible to decipher the structural relationships between different segments of the material accreted to Wyoming or the number of orogenic events involved. What is apparent, though, is that successive tracts of relatively primitive rocks were progressively accreted to the western margin of Laurentia during and following the 1.9-1.8 Ga growth of the continent and inclusion of Wyoming into Laurentia (Mueller et al. 2005b).

The collage of mainly metamorphosed arc-like igneous rocks and associated metasedimentary assemblages of the Selway terrane ranges in age from about 2.45 to 1.6 Ga in western Montana and central Idaho. Crust of this age extends southward to the southern part of the Idaho-Atlanta batholith in southwestern Idaho (e.g., Norman and Mertzman 1991), and into the Farmington Canyon complex in northern Utah. Farmington complex rocks include Precambrian metasedimentary rocks, quartzofeldspathic gneisses, and amphibolites (Hedge et al. 1983; Bryant 1988). Our recent U-Pb geochronology of zircons (via ion probe) extracted from lithologies within the layered metasedimentary succession indicate that, although, much of the detritus is likely to be Archean, younger (~2.4 Ga) zircons are also present, which demonstrate a Proterozoic (not Archean) depositional age for the protoliths (Mueller et al. 2004a). In addition, U-Pb ages of zircons extracted from orthogneisses in the northern part of the complex gave a distinct crystallization age of ~2.45 Ga as opposed to the age of ~1.8 Ga reported from discordant multi-grain zircon data by Hedge et al. (1983). U-Pb monazite and $^{40}Ar/^{39}Ar$ studies (e.g., Barnett et al. 1993; Nelson et al. 2002) indicate that these rocks experienced amphibolite facies metamorphism at ~1.8 Ga.

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