In suspect terrane? Provenance of the late Archean Phantom Lake metamorphic suite, Sierra Madre, Wyoming[1]

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Abstract: The 2.68 Ga Phantom Lake metamorphic suite of the Sierra Madre is a volcanogenic, volcaniclastic, and siliciclastic sequence that may have been deposited on or near the margin of the Wyoming Province or, alternatively, it may represent part of an exotic block accreted onto the southern margin of the Wyoming Province. The metamorphosed supracrustal rocks of the Phantom Lake metamorphic suite, along with quartzofeldspathic gneisses and granitoids of similar age, have light rare-earth element (LREE) – enriched REE patterns with little to no Eu-anomaly. These patterns are comparable to those of modern oceanic arc rocks and sediments. Both supracrustal and metaigneous rocks have radiogenic initial ε_{Nd} from +4.5 to –2.5 and Nd crustal residence ages between 2.7 and 3.0 Ga. It is proposed that these juvenile rocks were part of an intra-oceanic arc system formed beyond the influence of detritus from the Wyoming Province and subsequently were accreted onto the southern Wyoming Province following intrusion of granitic gneisses in the Sierra Madre at ca. 2.64 Ga. The younger 2.43 Ga Baggot Rocks granite has less radiogenic ε_{Nd} of –3.9 suggesting that the rocks of the Sierra Madre had accreted to the Wyoming Province by 2.43 Ga. The supracrustal sequences at South Pass, Bradley Peak, and the Rattlesnake Hills have similar, radiogenic initial Nd isotope compositions. Together with the Phantom Lake metamorphic suite, they represent juvenile additions to existing continental crust and provide evidence that lateral accretion of oceanic terranes was an important process of late Archean crustal growth in the Wyoming Province.

Résumé : La suite métamorphique de Phantom Lake, 2,68 Ga, dans la Sierra Madre est une séquence volcanogénique, volcanoclastique et silicoclastique qui a possiblement été déposée à la bordure ou à proximité de la bordure de la Province de Wyoming; la séquence pourrait aussi représenter une partie d'un bloc exotique qui a été accrété à la bordure sud de la Province de Wyoming. Les roches supracrustales métamorphisées de la suite métamorphique de Phantom Lake, tout comme des gneiss quartzo-feldspathiques et des granitoïdes d'âge semblable, ont des patrons de terres rares enrichis en éléments des terres rares légères, avec peu ou pas d'anomalie Eu. Ces patrons sont comparables à ceux de sédiments et de roches d'arcs océaniques modernes. Les roches supracrustales et les roches méta-ignées ont toutes des valeurs ε_{Nd} radiogéniques initiales de +4,5 à –2,5 et des âges de résidence dans la croûte entre 2,7 et 3,0 Ga. Selon nous, ces roches juvéniles faisaient partie d'un système d'arc intra-océanique formé au-delà de l'influence des débris de la Province de Wyoming et elles ont été par la suite accrétées au sud de la Province de Wyoming après l'intrusion de gneiss granitiques dans la Sierra Madre vers 2,64 Ga. Le granite de Baggot Rocks, plus jeune, a des valeurs ε_{Nd} radiogéniques inférieures de –3,9 suggérant que les roches de la Sierra Madre étaient déjà accrétées à la Province de Wyoming à 2,43 Ga. Les séquences supracrustales à South Pass, Bradley Peak et aux Rattlesnake Hills ont des compositions initiales en isotopes du Nd similaires. Avec la suite métamorphique de Phantom Lake, elles représentent des ajouts juvéniles à la croûte continentale existante et fournissent des preuves que l'accrétion latérale de terranes océaniques était un processus important de croissance de la croûte à l'Archéen tardif dans la Province de Wyoming.

[Traduit par la Rédaction]

Introduction

Lateral growth of the continents by accretion of juvenile terranes has been an important means of crustal growth throughout geologic time. Phanerozoic examples include the Wrangellia terrane of the Canadian Cordillera (Samson and Patchett 1991), the Brook Street terrane of New Zealand (Frost and Coombs 1989), and the outboard terranes of the Klamath Mountains of the western United States (Irwin 1981). Crustal growth by lateral accretion also is documented for several Archean cratons including the Superior (Card 1990; Percival et al. 1994; Puchtel et al. 1998; Polat and Kerrich 2001),

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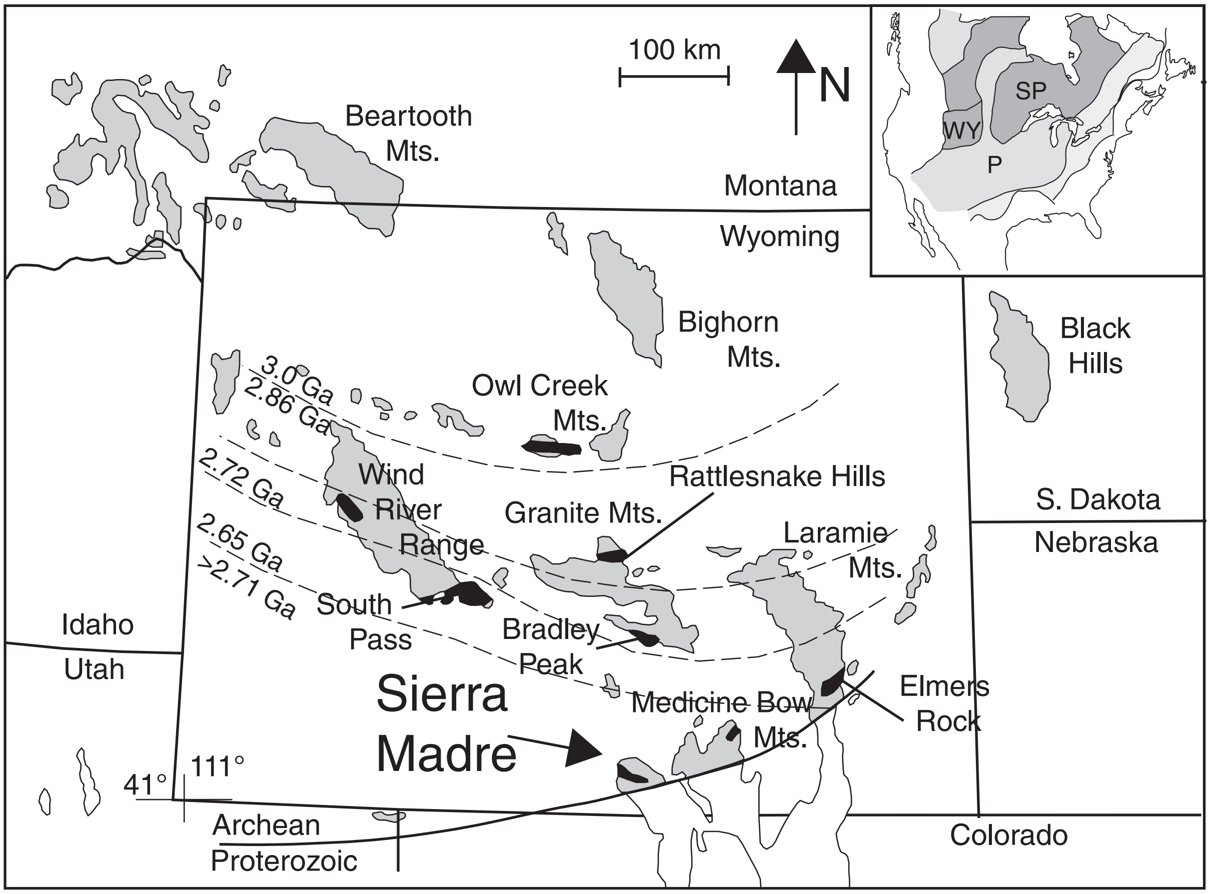
Fig. 1. Map of the Archean Wyoming Province. The thick black line separates Archean rocks of the Wyoming Province from Proterozoic rocks. Archean-cored Laramide uplifts are shown in gray. Archean supracrustal successions discussed in this paper are shaded black. The thin dashed lines mark the boundaries of the supracrustal belts described by Chamberlain et al. (2003).



Slave (Kusky 1989; Davis and Hegner 1992), Yilgarn (Myers 1995; Kusky and Polat 1999), and Pilbara (Van Kranendonk et al. 2002); yet debate persists as to whether the crust grew by modern tectonic processes such as arc-accretion or if crustal growth was dominated by magmatic addition (Hamilton 1998). This study documents that lateral accretion of oceanic terranes is an important process of late Archean crustal growth along the southern margin of the Wyoming Province.

The 500 000 km^2 Archean Wyoming Province includes some of the oldest rocks (>3.4 Ga) in North America (Fig. 1) (Mueller et al. 1996). Growth by magma addition is well documented for the Archean Wyoming Province (Frost et al. 1998). More recently, Chamberlain et al. (2003) proposed that horizontal convergence and amalgamation processes also affected the southern margin of the province in late Archean time. However, it is unclear whether the accretion of these terranes involved any net crustal growth.

In this study, we examine the Phantom Lake metamorphic suite and underlying Vulcan Mountain metavolcanics and quartzofeldspathic gneiss, located in the Sierra Madre and Medicine Bow Mountains of southeastern Wyoming, as a possible example of an oceanic terrane accreted onto the Wyoming craton during the late Archean.

Geologic setting

The Sierra Madre is a northwest-striking Laramide uplift of Archean and Proterozoic rocks located in southern Wyoming to the west of the Medicine Bow Mountains (Houston et al. 1968) (Figs. 1, 2). The Sierra Madre and Medicine Bow Mountains are interpreted to record a shared Precambrian geologic history (Houston et al. 1992 and references therein). These uplifts expose an extensive succession of late Archean – Early Proterozoic metasedimentary and metavolcanic rocks (Houston et al. 1992) (Fig. 3). The Archean exposures are bounded on the south by the Cheyenne belt, which is a ca. 1.78 Ga shear zone extending through the central Sierra Madre and Medicine Bow Mountains. This shear zone marks the southern boundary of the late Archean Wyoming Province and is interpreted as the suture between Archean rocks of the Wyoming Province and Proterozoic accreted island arcs (Houston et al. 1979; Duebendorfer and Houston 1987, 1990) (Fig. 1).

The oldest rocks of the Archean Wyoming Province are exposed in the central and northern parts of the craton (Fig. 1). These rocks of early to middle Archean age were formed by ca. 2.8 Ga and they have experienced little to no subsequent deformation (Frost et al. 1998, 2006*a*; Frost and Fanning

Fig. 2. (A) Generalized geological map of the Sierra Madre and Medicine Bow Mountains, after Houston (1993). The main study area in the northwest Sierra Madre is outlined. Locations for samples collected outside the designated study area are shown. (B) Geologic map of the study area in the northwest Sierra Madre, showing major geologic units and locations of samples.

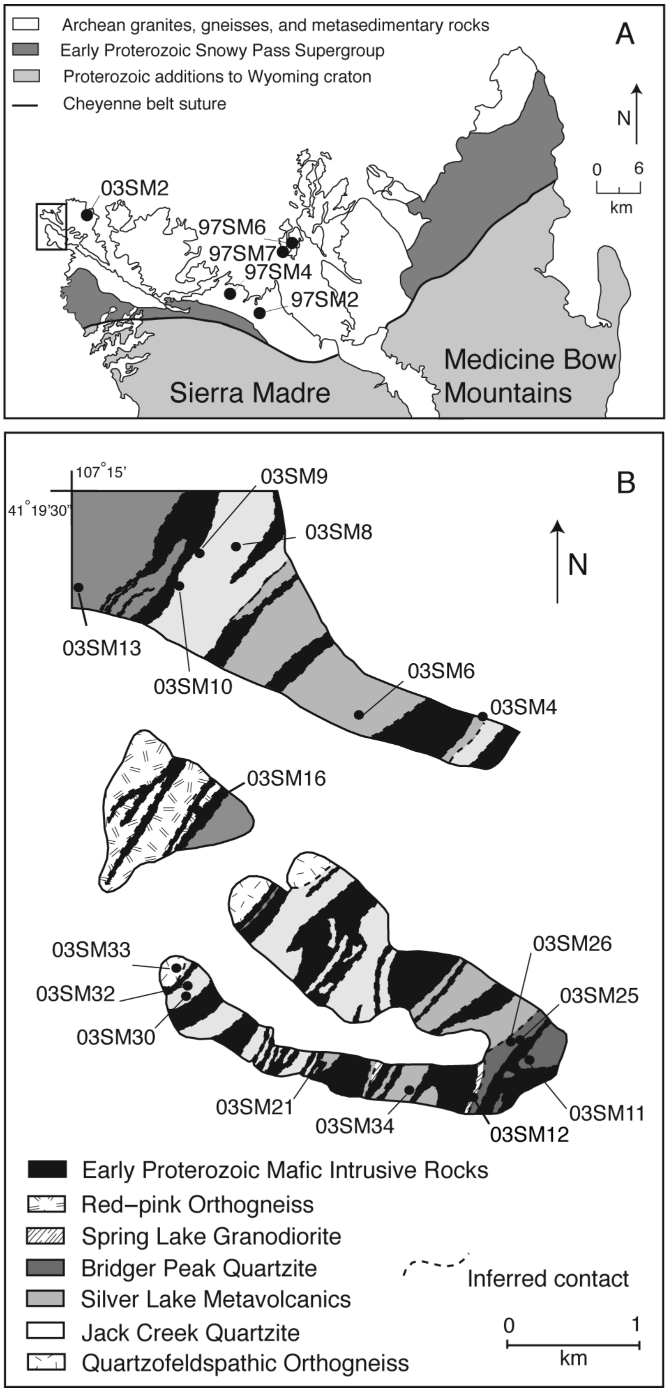
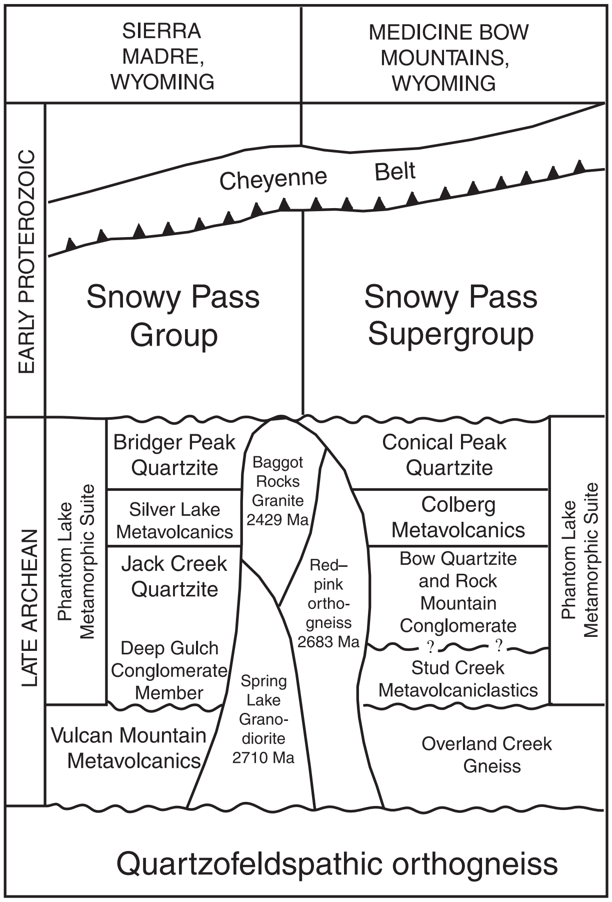


Fig. 3. Late Archean and Early Proterozoic stratigraphy of the Sierra Madre and Medicine Bow mountains (after Houston et al. 1992).



2006). A series of east–west-trending supracrustal belts lie to the south and are exposed in the Granite Mountains, Wind River Mountains, Seminoe Mountains, and Laramie Mountains, as well as the Sierra Madre and Medicine Bow Mountains. The ages of the supracrustal belts are generally young from north to south, from ca. 2.86 to ca. 2.65 Ga; however, the southernmost exposures in the Sierra Madre and Medicine Bow Mountains appear to be older, although they are not dated directly (Chamberlain et al. 2003 and references therein) (Fig. 1).

The southern margin of the Wyoming Province was intruded by granitic magmas at 2.72–2.67, 2.63–2.60, and 2.55–2.50 Ga (Frost et al. 1998; Chamberlain et al. 2003). In the Sierra Madre, the oldest of these three pulses is recorded by the 2710 ± 10 Ma Spring Lake granodiorite and the 2683 ± 6 Ma red–pink orthogneiss (Premo and Van Schmus 1989). No igneous rocks of 2.55–2.50 Ga age are known from the Sierra Madre although the Baggot Rocks granite was intruded at 2429 ± 4 Ma (Premo and Van Schmus 1989). This paper identifies an additional ca. 2.64 Ga intrusive unit.

The Archean rocks of the Sierra Madre have been subjected to extensive Proterozoic tectonism. The ca. 2.43 Ga Baggot Rocks granite represents the only documented magmatism in the Wyoming Province during this time period (Premo and Van Schmus 1989). Proterozoic rifting along the southern continental margin at ca. 2.1 Ga is evidenced by the intrusion of mafic dykes and deposition of a passive margin sequence (Cox et al. 2000; Karlstrom et al. 1981, 1983). Proterozoic island-arc plutonic and volcanic rocks south of the Cheyenne belt have been determined to be no older than ca. 1810 Ma (Premo and Van Schmus 1989; Premo and Fanning 2000; Premo and Loucks 2000).

Various interpretations have been proposed for the provenance of the Phantom Lake metamorphic suite; this is an assemblage of volcanogenic, volcaniclastic, and coarse clastic sediments isoclinally folded and metamorphosed to amphibolite facies that occurs in both the Sierra Madre and Medecine Bow areas, but with different subdivisions (Fig. 3). Hills et al. (1975) and Graff (1978) interpreted the Phantom Lake metamorphic suite to be deposited on the southern margin of the Wyoming Province in a fluvial to shallow-marine environment. Later workers suggested that deposition of the supracrustal succession was in fluvial to shallow-marine basins along the southern margin of the Wyoming Province or along the margin of an Archean microplate subsequently accreted to the Archean Wyoming craton (Karlstrom et al. 1981; Houston et al. 1992; Houston 1993). Chamberlain et al. (2003) raised the possibility that the rocks of the Sierra Madre and Medicine Bow Mountains are an exotic terrane accreted to the southern margin of the Wyoming Province ca. 2.62 Ga or later. This interpretation is based on the lithological differences among the supracrustal successions of the Sierra Madre and Medicine Bow Mountains and other supracrustal belts elsewhere in the Wyoming Province. There is an apparent reversal in the southward-younging trend of the ages of supracrustal belts in the Wyoming Province (Fig. 1) and slightly less-evolved Pb isotope compositions for igneous feldspars from the Sierra Madre when compared with those from other plutonic rocks from the Wyoming Province (Harper 1997).

Archean rocks of the Sierra Madre

Almost 100 years of geological investigation summarized by Houston et al. (1992) has established the following lithologic units and provisional stratigraphy for rocks of the Sierra Madre (Fig. 3).

The proposed Archean basement in the Sierra Madre is a quartzofeldspathic gneiss composed of unknown proportions of orthogneiss and paragneiss. It is undated, but looks similar in appearance to the 2.71 Ga Spring Lake granodiorite (Premo and Van Schmus 1989).

Two supracrustal sequences are interpreted to overlie the quartzofeldspathic basement gneiss: the Vulcan Mountain metavolcanics, and the Phantom Lake metamorphic suite (Karlstrom et al. 1981; Houston et al. 1992) (Fig. 3). The amphibolite facies, metamorphosed mafic volcanic, and sedimentary rocks of the Vulcan Mountain metavolcanics are interpreted to unconformably underlie the Phantom Lake metamorphic suite. Lithologies include metabasalt, hornblende gneiss, mafic volcaniclastic rocks, biotite schist, subargillaceous quartzite, and marble (Houston et al. 1992). These rocks are correlated with the Overland Creek gneiss of the Medicine Bow Mountains (Fig. 3). The Vulcan Mountain metavolcanics are at least late Archean in age, based on the crosscutting relationship of the ca. 2.71 Ga Spring Lake granodiorite (Premo and Van Schmus 1989). Harper (1997) reported a ca. 2.69 Ga U–Pb titanite age from a volcanic or volcaniclastic rock from the Vulcan Mountain metavolcanics and interpreted this date as recording a regional metamorphic event.

Previous workers interpreted the Phantom Lake metamorphic suite as a threefold supracrustal succession consisting of the Jack Creek quartzite, the Silver Lake metavolcanics, and the Bridger Peak quartzite (Fig. 3). The Phantom Lake metamorphic suite has an estimated thickness of 2 km and contains approximately 60% metavolcanic rocks and 40% siliciclastic rocks. All units have been metamorphosed to amphibolite facies (Houston et al. 1992).

The Jack Creek quartzite is interpreted as the lowest stratigraphic unit of the Phantom Lake metamorphic suite. It is divided into the basal Deep Gulch conglomerate and the upper Jack Creek quartzite. The conglomeratic basal layer contains arkosic quartzite with beds of radioactive quartz-pebble conglomerate, and it is interpreted as a fluvial deposit (Kratochvil 1981). The Jack Creek quartzite consists of arkosic subargillaceous quartzite, phyllite, metacarbonate, quartz-pebble conglomerate, and metagraywacke (Graff 1978; Houston et al. 1992). Large-scale cross-beds, herringbone cross-stratification, and small planar cross-beds have been identified in the Jack Creek quartzite. Based on preserved sedimentary structures, interbedded phyllite and metacarbonate, and dispersed bimodal paleocurrent directions, the depositional environment of the upper Jack Creek quartzite is interpreted as shallow marine (Houston et al. 1992). The Jack Creek quartzite is correlated with the Stud Creek and Bow quartzite of the Medicine Bow Mountains (Fig. 3).

Disconformably above the Jack Creek quartzite are the Silver Lake metavolcanics. Metagraywacke, metatuff, biotite schist, paraconglomerate, quartzite, and carbonate rocks dominate, but there are also minor volumes of metabasalt. Fine-grained lithologies and fewer basalt flows are found in the Silver Lake metavolcanics of the Sierra Madre than in the correlative Colberg metavolcanics in the Medicine Bow Mountains (Houston et al. 1992; Houston et al. 1993). The depositional environment for this unit is interpreted as shallow marine with subaerial volcanism depositing lava and tuff to adjacent basins. Deposition is thought to be rapid owing to changes in lithology. Uplift and erosion of a granitic source coincident with volcanism could account for the deposition of the paraconglomerate unit within the Silver Lake metavolcanics (Houston et al. 1992).

The Bridger Peak quartzite is the youngest unit of the Phantom Lake metamorphic suite. It lies disconformably above the Silver Lake metavolcanics and unconformably below the Proterozoic Snowy Pass Supergroup. Fine-grained white quartzite and phyllitic layers dominate the unit, although minor metacarbonate, pebble conglomerate, and metavolcanic rock have been documented. The depositional environment and age of the Bridger Peak quartzite are uncertain (Houston et al. 1992). The Bridger Peak quartzite is correlated with the Conical Peak quartzite of the Medicine Bow Mountains (Fig. 3), which is interpreted to be deposited in a fluvial to shallow-marine environment (Houston et al. 1992).

The Phantom Lake suite, Vulcan Mountain metavolcanics, and the quartzofeldspathic gneiss basement have all undergone intense folding and deformation producing recumbent folds and nappe structures from regional to map scale. This deformation obscures the stratigraphic identification and order of the three principal units (Houston et al. 1992, 1993; Houston 1993). The 2.71 Ga Spring Lake granodiorite is interpreted to intrude the Jack Creek quartzite and also possibly the Silver Lake metavolcanics in the Sierra Madre

(Karlstrom et al. 1981; Houston et al. 1992, 1993; Houston 1993). If these interpretations are correct, the lower portion of the Phantom Lake metamorphic suite is at least 2710 Ma. Deformation of the Phantom Lake metamorphic suite and other associated rocks ceased before deposition of the less-deformed overlying Snowy Pass Supergroup and the emplacement of the ca. 2.43 Ga Baggot Rocks granite (Houston et al. 1993). The 2683 ± 6 Ma red–pink orthogneiss (Premo and Van Schmus 1989) has uncertain field relations to the other rocks of the Sierra Madre (Houston et al. 1992).

Sample descriptions

Representative samples from the Phantom Lake metamorphic suite and associated Archean plutonic units of the Sierra Madre were collected for geochemical and isotopic analysis (Tables 1–3). Most samples were collected from the northwest end of the uplift where the effects of Proterozoic deformation are least pronounced. Sample locations are shown in Fig. 2 and geographic coordinates are listed in Souders (2004).

Jack Creek quartzite

Three quartzites (03SM10, 30, 32), one schist (03SM8), and two calcareous metasedimentary rocks (03SM2, 9) were collected and analyzed from the Jack Creek quartzite. The three quartzites are arkosic with scant amounts of biotite and muscovite. Sample 03SM10 was sampled from the conglomeratic Deep Gulch Member of the Jack Creek quartzite and contains medium-grained quartz and feldspar grains. Samples 03SM30 and 03SM32 were collected from the upper portion of the Jack Creek quartzite. Sample 03SM30 consists of large grains of both microcline and plagioclase in a quartz-rich matrix. Sample 03SM32 is composed of clasts of microcline and plagioclase surrounded by quartz and layers of muscovite and biotite. Schist sample 03SM8 contains both biotite and muscovite with quartz, feldspar, and chlorite. Sample 03SM9 contains continuous layers of biotite along with quartz, feldspar, muscovite, calcite, and epidote. Sample 03SM2 is composed of foliated hornblende and actinolite layers with minor calcite, quartz, and plagioclase.

Silver Lake metavolcanics

Samples examined from the Silver Lake metavolcanics include a metadacite (03SM6), two metapsammites (03SM4, 21), and a calcareous metasedimentary rock (03SM34). In sample 03SM6, relic igneous euhedral plagioclase is preserved within a fine-grained matrix of mica, quartz, and feldspar. Samples 03SM4 and 03SM21 are both fine-grained rocks with obvious mica layering around larger grains of plagioclase, orthoclase, and quartz. Sample 03SM34 is also fine grained, and chiefly composed of plagioclase, hornblende, and biotite with minor amounts of quartz and calcite.

Bridger Peak quartzite

Three quartzite samples were analyzed from the Bridger Peak quartzite. Samples 03SM25 and 03SM26 are both quartz arenites with minor amounts of muscovite and microcline. Sample 03SM11 is a quartz arkose containing abundant quartz, feldspars altered to zoesite, and biotite. In the field, these samples are indistinguishable in appearance from quartzites within the Jack Creek quartzite.

Granitoids and gneisses

The quartzofeldspathic basement gneiss was sampled at two locations. Both samples (03SM13, 33) are foliated and contain abundant biotite with minor amounts of hornblende. Samples 03SM16 and 03SM18 are from the red–pink orthogneiss and have large microcline phenocrysts along with biotite, chlorite, epidote, and quartz. Sample 03SM12 was sampled from a location mapped as the Spring Lake granodiorite. The appearance and mineralogy of this sample is similar to that of the quartzofeldspathic orthogneiss. Houston et al. (1992) noted that in some areas within the Sierra Madre it is difficult to distinguish between the foliated rocks of the quartzofeldspathic basement and the Spring Lake granodiorite. Other gneisses and granitoids included in this study were collected in the eastern Sierra Madre and around Baggot Rocks (97SM2, 4, 6, 7) (Fig. 2). These rocks are all foliated granitoids with varying amounts of quartz, plagioclase, orthoclase, and biotite.

Geochemical data

Supracrustal rocks

The SiO_2 content of the metasedimentary rocks varies from 54.5% to 97.23% and Al_2O_3 from 1.45% to 19.3% (Table 1). In general, the fine-grained samples have higher Al_2O_3 than the coarser grained quartzites, reflecting the concentration of clays in the fine-grained rocks. The chemical index of alteration for the metasedimentary samples falls between 30 and 69, with 50 being the average for unweathered upper continental crust and 70–75 the average value for shale (Nesbitt and Young 1982, 1984).

The rare-earth element (REE) patterns for the metasedimentary rocks are slightly light REE (LREE) enriched (La_n/Sm_n = 1.5–4.3) and display relatively modest heavy REE (HREE) depletion (Gd_n/Yb_n = 1.7–4.2) (Figs. 4*a*–4*c*). There are no appreciable Eu anomalies (Eu/Eu* = 0.7–1.1). The ΣREE for two of the Bridger Peak quartzite samples are considerably lower than the other samples (Table 1; Fig. 4*c*) and are interpreted as the result of quartz dilution in these very siliceous samples. The REE patterns of all the metasedimentary samples are distinct from the flat REE patterns of rocks derived from a mid-ocean ridge basalt source, the LREE-enriched and severely HREE-depleted patterns of Na-rich granitoids, and the LREE-enriched pattern with pronounced negative Eu anomaly of post-Archean upper continental crust (Taylor and McLennan 1985).

The metadacite sampled from the Spring Lake metavolcanics has 71% SiO_2 and $Na_2O + CaO > K_2O$. Based on the classification scheme presented in B.R. Frost et al. (2001), this sample is magnesian, calc-alkalic, and peraluminous (Fig. 5). The metadacite sample has a chemical index of alteration value of 51.5.

Granitoids and gneisses

The SiO_2 content of granitoid and gneiss samples varies only between 65.3% and 66.4% (Table 1). The red–pink orthogneiss has the highest K_2O values (K_2O = 3.7%–4.3%). The Spring Lake granodiorite has the highest Na_2O with 5.2%. Both the Spring Lake granodiorite and the quartzofeldspathic basement gneiss have low K_2O (<3%) and high Na_2O (>4%) similar to Archean tonalites and trondhjemites.

Table 1. Chemical analyses from the Sierra Madre, southern Wyoming.

	Supracrustal rocks										
Sample:	03SM2	03SM8	03SM9	03SM10	03SM30	03SM32	03SM4	03SM6	03SM21	03SM34	03SM11
Unit:	Wj	Wj	Wj	Wj	Wj	Wj	Ws	Ws	Ws	Ws	Wbp
Lithology:	CM	S	CM	Q	Q	Q	MP	metadacite	MP	CM	Q
SiO_2	54.5	58.8	66.4	81.8	82.73	78	65.5	70.9	69.6	55.1	80.6
TiO_2	0.22	6.06	2.39	1.35	4.36	3.26	2.32	1.1	3.01	2.27	1.87
Al_2O_3	11.7	19.3	15.1	10.2	9.34	11.37	15.6	15.4	15	14.52	10.2
Fe_2O_3	12.3	0.27	2.46	0.24	0.06	0.2	2.6	1.55	0.98	6.23	4.19
MnO	2.65	0.94	4.03	4.32	2.1	2.55	4.3	5.65	3.81	4.5	0.13
MgO	9.13	7.1	5.05	0.78	0.47	2.61	4.4	2.95	3.39	7.96	1.35
CaO	0.63	0.85	0.55	0.28	0.12	0.26	0.41	0.44	0.63	0.62	0.14
Na_2O	0.17	0.04	0.04	0.01	<0.01	0.01	0.06	0.03	0.03	0.13	0.03
K_2O	4.03	3.03	2.19	1.09	0.2	1.04	2.94	1.44	2.08	5.59	1.05
P_2O_5	0.09	0.13	0.19	0.05	0.02	0.06	0.15	0.13	0.08	0.46	0.07
Cr_2O_3	0.02	0.02	<0.01	<0.01	0.03	0.03	0.01	<0.01	0.02	0.03	<0.01
LOI	5.24	3.11	1.4	0.78	0.6	0.65	1.19	1.44	1.44	1.85	1.25
Sum	100.7	99.6	99.8	100.8	100.2	100.2	99.4	101.1	100	99.6	100.8
Rb	1.47	211.13	71.67	36.90	94.63	111.31	78.12	35.5	90.75	131	77.62
Sr	171.08	80.94	267.56	61.86	82.08	145.30	584.47	4	116.96	1410	224.11
Ba	312.77	593.99	481.16	384.23	861.51	775.64	873.02	1340	798.20	184	594.77
Zr	71.34	151.91	134.96	77.81	60.07	144.22	95.99	124	193.30	134	94.00
Y	13.92	17.28	9.33	3.70	6.53	6.09	5.47	7.4	14.81	20.3	9.69
Ni	79.21	99.99	61.53	25.09	9.41	38.28	82.60	13	64.91	65	19.06
Cr	101.90	195.90	73.93	42.47	22.16	58.73	114.96	23	128.65	231	39.36
V	249.61	505.49	355.30	262.84	444.00	699.80	315.80	54	527.39	136	511.40
Sc	18.18	20.09	11.13	5.70	1.21	4.59	7.22	<5	12.95	18	2.98
Pb	16.86	19.95	6.90	3.04	6.37	5.19	20.99	6	6.15	24	10.13
Th	6.22	13.68	4.41	7.93	7.24	7.21	4.45	9.8	11.45	17.6	4.69
U	1.46	2.96	1.07	0.77	1.81	0.93	0.80	2.52	4.61	3.71	1.25
La	18.35	48.57	16.96	18.46	8.59	13.86	13.10	32.5	28.50	72.9	13.60
Ce	32.70	93.72	37.54	37.01	19.46	28.43	28.13	60	56.78	143	30.53
Pr	4.05	10.96	4.48	4.31	2.56	3.57	3.22	6.78	6.88	17.8	3.96
Nd	14.26	36.42	15.20	14.21	9.39	12.62	10.63	24.5	23.12	64	13.87
Sm	2.80	6.46	2.65	2.12	2.41	2.08	1.75	4	4.10	10.8	2.53
Eu	0.85	1.62	0.95	0.54	0.65	0.67	0.65	1.28	1.16	2.75	0.66
Gd	2.90	6.04	2.61	1.75	2.28	1.75	1.97	3.22	3.83	8.97	2.46
Tb	0.45	0.77	0.33	0.18	0.30	0.23	0.20	0.41	0.51	1.08	0.33
Dy	2.49	3.46	1.66	0.70	1.32	1.09	0.96	1.59	2.61	4.41	1.65
Ho	0.52	0.65	0.34	0.13	0.24	0.22	0.20	0.27	0.54	0.71	0.34
Er	1.49	1.73	0.97	0.39	0.62	0.63	0.60	0.61	1.59	1.84	0.98
Tm	0.22	0.24	0.15	0.06	0.09	0.10	0.10	0.09	0.24	0.24	0.15
Yb	1.42	1.59	0.97	0.40	0.57	0.63	0.70	0.6	1.58	1.8	1.00
Lu	0.22	0.28	0.16	0.08	0.12	0.13	0.15	0.09	0.28	0.2	0.19
ΣREE	82.73	212.50	84.99	80.36	48.60	66.00	62.35	135.94	131.72	330.5	72.25
CIA	30.26	69.18	52.45	53.11	53.00	58.44	52.15	—	57.02	—	50.86
Eu/Eu*	0.92	0.80	1.11	0.87	0.85	1.08	1.08	1.10	0.90	0.86	0.81
La(n)/Sm(n)	3.76	4.31	3.67	5.00	2.04	3.82	4.28	4.66	3.99	3.87	3.08
Gd(n)/Yb(n)	1.73	3.22	2.28	3.68	3.38	2.35	2.39	4.54	2.05	4.22	2.07
La(n)/Yb(n)	8.34	19.80	11.33	29.66	9.73	14.26	12.16	35.05	11.65	26.21	8.76

Note: Analyses for major elements for all samples, and trace elements and rare-earth elements (REE) for metaigneous rocks performed at XRAL Laboratories, rocks performed at the University of Wyoming by inductively coupled plasma – mass spectrometry (ICP–MS). X-ray fluorescence analysis on all major oxides is Spring Lake granodiorite; Wgn, quartzofeldspathic gneiss; Wg, red–pink orthogneiss; CM, calcareous metasedimentary rock; S, schist; Q, quartzite; MP,

			Crystalline rocks				
03SM25	03SM26	DUP–035M25	03SM12	03SM13	03SM33	03SM16	03SM18
Wbp	Wbp	Wbp	Wsl	Wgn	Wgn	Wg	Wg
Q	Q	Q	granodiorite	orthogneiss	orthogneiss	orthogneiss	orthogneiss
97.09	88.56	97.23	66.4	66.4	66.08	65.3	65.9
0.82	3	0.82	2.89	2.1	2.61	3.73	4.32
1.46	5.65	1.45	14.8	15.1	15.3	14.5	14.5
0.02	0.06	0.03	2.34	3.69	1.36	2.99	2.19
0.04	0.22	0.04	5.23	4.64	4.1	3.99	4.11
0.34	1.32	0.34	3.78	5.07	5.06	4.62	4.21
0.05	0.1	0.05	0.38	0.5	0.47	0.49	0.44
<0.01	<0.01	<0.01	0.08	0.07	0.05	0.08	0.08
0.14	0.34	0.14	2.53	2.87	3.43	2.52	2.22
<0.01	0.02	<0.01	0.16	0.19	0.2	0.19	0.14
0.03	0.04	0.03	<0.01	0.01	0.03	<0.01	<0.01
0.25	0.75	0.15	0.82	1.33	1.25	1.12	0.88
100.3	100.2	100.3	99.4	102	100.2	99.6	99
21.60	77.38	—	79.7	81.3	115	148	156
7.06	36.12	—	3.5	4.8	268	5.6	4.4
175.91	818.55	—	1390	974	118	1550	2360
24.78	101.85	—	117	116	246	135	119
1.47	3.62	—	6.8	12.2	11	12.1	10.1
4.36	18.42	—	54	28	30	26	25
13.25	37.26	—	99	77	196	91	82
209.43	321.66	—	67	94	86	85	70
0.60	1.52	—	7	11	11	11	8
12.22	25.41	—	7	21	11	33	18
2.03	4.01	—	5.5	8.1	13.9	11.8	13.6
0.29	1.05	—	1.54	2.6	1.22	3.47	2.39
2.02	1.88	—	25.3	33.7	33.1	48.1	34.7
3.43	4.03	—	48.5	69	61.8	84.4	66.7
0.61	0.65	—	5.68	7.8	7.33	9.46	7.3
2.16	2.71	—	21.2	28.9	25.1	33	25.7
0.44	0.70	—	3.5	4.8	4.2	5.6	4.4
0.10	0.26	—	1.24	1.4	1.15	1.45	1.38
0.37	0.77	—	2.78	4.15	3.9	4.08	3.39
0.05	0.11	—	0.37	0.58	0.48	0.55	0.5
0.26	0.57	—	1.44	2.47	2.11	2.51	2.1
0.05	0.12	—	0.25	0.49	0.37	0.47	0.39
0.15	0.36	—	0.62	1.27	1.13	1.22	1.03
0.02	0.06	—	0.1	0.18	0.17	0.19	0.16
0.16	0.41	—	0.6	1.3	1.2	1.3	1.1
0.03	0.09	—	0.09	0.19	0.16	0.2	0.14
9.87	12.73	—	111.67	156.23	142.2	192.53	148.99
59.60	60.31		—	—	—	—	—
0.73	1.10	—	1.23	0.97	0.88	0.94	1.10
2.64	1.54	—	4.15	4.03	4.52	4.93	4.52
1.98	1.59	—	3.92	2.70	2.75	2.66	2.61
8.22	2.96	—	27.28	16.77	17.85	23.94	20.41

Don Mills, Ontario, on solutions prepared from samples powdered in a tungsten carbide mill. Analyses for trace elements and REE for metasedimentary in wt.%. ICP–MS analysis on all trace elements is in ppm. Wj, Jack Creek quartzite; Ws, Silver Lake metavolcanics; Wbp, Bridger Peak quartzite; Wsl, metapsammite; CIA, chemical index of alteration = $Al_2O_3/(Al_2O_3 + Na_2O + CaO)*100$; Eu/Eu* = $Eu(n)/(Sm(n)*Gd(n))^{0.5}$; n, normalized to chondrites.

Table 2. U–Pb data for rocks of the Sierra Madre, southern Wyoming.

		Concentration (ppm)										Ages (Ma)						
Fraction (n)	Weight (mg)	U	Pb (rad)	$\frac{Th}{U}$	$\frac{^{206}Pb}{^{204}Pb}$ [a]	$\frac{^{206}Pb}{^{238}U}$ [b]	Error (%)	$\frac{^{207}Pb}{^{235}U}$ [b]	Error (%)	$\frac{^{207}Pb}{^{206}Pb}$ [b]	Error (%)	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$ error (±Ma)	Corr. coeff.	Total common Pb (pg)	Discordance (%)
Sample 03SM13, quartzofeldspathic orthogneiss																		
A	0.005	62.8	31.69	0.58	1498.05	0.42585	0.59	10.4959	0.6	0.17876	0.11	2287	2479.6	2641.4	1.8	0.98	5.6	15.9
B	0.005	110.1	58.21	0.61	998.18	0.43261	0.35	10.718	0.4	0.17969	0.11	2317.5	2499	2650	1.8	0.96	13.9	14.9
C	0.005	219.7	102.78	0.54	2326.41	0.39185	0.21	9.6499	0.2	0.17861	0.1	2131.4	2401.9	2640	1.7	0.91	10.8	22.6
D	0.005	191.3	94.17	0.54	4099.98	0.41934	0.23	10.3408	0.3	0.17885	0.1	2257.5	2465.8	2642.2	1.6	0.93	6.1	17.2
F	0.005	222.9	90.01	0.45	3097.6	0.34382	0.26	8.36	0.3	0.17635	0.1	1905	2270.8	2618.8	1.7	0.93	7.5	31.4
G	0.009	161.9	83.31	0.58	6057.84	0.43767	0.21	10.765	0.3	0.17839	0.13	2340.2	2503	2638	2.2	0.84	6.5	13.4
H	0.009	121.1	55.17	0.47	2764.03	0.38918	0.25	9.6447	0.3	0.17973	0.1	2119	2401.4	2650.4	1.7	0.92	9.1	23.5
I	0.009	144.3	69.41	0.59	2577.56	0.39928	0.2	9.8132	0.2	0.17825	0.1	2165.7	2417.4	2636.7	1.7	0.9	11.7	21
Sample 03SM6, metadacite																		
A	0.0045	60.2	34.99	0.85	3250.49	0.46779	0.99	11.7972	1	0.18291	0.1	2473.8	2588.4	2679.4	1.7	0.99	2.5	9.2
B	0.005	80.3	36.49	0.66	2944.67	0.36633	0.53	9.2595	0.5	0.18332	0.1	2021.1	2364	2683.1	1.6	0.98	3.2	29
D	0.0047	64.8	21.4	0.58	1623	0.26324	0.31	6.7201	0.3	0.18515	0.11	1506.4	2075.3	2699.6	1.9	0.94	3.2	49.4
E	0.0045	87.5	18.88	0.5	1675.29	0.17115	0.79	4.2714	0.8	0.181	0.11	1018.5	1687.9	2662.1	1.8	0.99	2.6	66.5
F	0.0048	51.4	21.97	0.34	1865.86	0.3509	0.69	8.781	0.7	0.18149	0.25	1938.9	2315.5	2666.5	4.2	0.94	3	31.5

Note: For fractions with total common Pb >5 pg, corrections were made using Stacey and Kramers (1975) initial Pb. Analysis accomplished with a VG Sector 54 thermal ionization mass spectrometer at the University of North Carolina, Chapel Hill. Decay constants used are $^{238}U = 0.155125 \times 10^{-9}$ year^{-1} and $^{235}U = 0.98485 \times 10^{-9}$ year^{-1} (Steiger and Jäger 1977). Weights are estimated using a video camera and scale, and are known to within 10%. Data reduction and error analysis was accomplished using PbMacDat-2 by D.S. Coleman, using the algorithms of Ludwig (1989, 1990). All errors are reported in % at the 2σ confidence interval.

[a] Measured ratio corrected for fractionation only. All Pb isotope ratios were measured using the Daly detector and are corrected for mass fractionation using 0.18%/amu (atomic mass units).

[b] Corrected for fractionation, spike, blank, and initial common Pb. After subtraction of blank Pb (<5 pg), common Pb corrections were unnecessary for all fractions from sample 03SM6.

Table 3. Nd isotopic data for rocks of the Sierra Madre, southern Wyoming.

Sample	Unit	Sm (ppm)	Nd (ppm)	$\frac{^{147}\mathrm{Sm}}{^{144}\mathrm{Nd}}$	$\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}$	Initial $\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}$	Initial $\varepsilon_{\mathrm{Nd}}$	T_{CR} (Ga)
Supracrustal rocks, initial ratios calculated for 2.68 Ga								
03SM2	Wj	3.57	18.27	0.118	0.511265	0.509176	0.4	3
03SM8	Wj	6.71	37.23	0.10898	0.511195	0.509265	2.1	2.8
03SM8[a]	Wj	7.35	42.42	0.10471	0.511142	0.509288	2.6	2.8
03SM9	Wj	2.85	15.93	0.10813	0.511123	0.509209	1	2.9
03SM10	Wj	2.63	17.5	0.09087	0.510981	0.509373	4.3	2.7
03SM10[b]	Wj	2.84	18.18	0.09456	0.510934	0.50926	2	2.8
03SM30	Wj	2.36	9.35	0.15257	0.511845	0.509144	–0.2	
03SM32	Wj	1.83	11.11	0.09973	0.510972	0.509206	1	2.9
03SM4	Ws	2.28	13.46	0.10237	0.511196	0.509384	4.5	2.7
03SM6	Ws	4.03	24.61	0.09897	0.511029	0.509276	2.4	2.8
03SM21[a]	Ws	4.43	24.31	0.11027	0.511186	0.509234	1.5	2.9
03SM34	Ws	11.6	69.21	0.10135	0.511056	0.509262	2.1	2.8
03SM34	Ws	12.42	75.65	0.09928	0.511051	0.509293	2.7	2.8
03SM11	Wbp	2.54	14.18	0.10825	0.511193	0.509277	2.4	2.8
03SM25[b]	Wbp	0.47	2.42	0.11691	0.511375	0.509306	2.9	2.8
03SM26[b]	Wbp	0.83	3.29	0.15233	0.511727	0.509031	–2.5	
Granitoids and gneisses, initial ratios calculated for 2.68 Ga								
03SM16	Wg	5.21	31.22	0.10092	0.511001	0.509214	1.1	2.9
03SM13	Wgn	4.78	28.92	0.09985	0.511029	0.5092618	2.1	2.8
03SM33	Wgn	4.53	28.15	0.0973	0.511034	0.5093119	3.1	2.8
97SM2	Wgn	1.45	9.46	0.09235	0.510835	0.5092	0.9	2.9
97SM7	Wgn	4.55	27.92	0.09856	0.51095	0.509205	1	2.9
03SM12	Wsl	4.09	24.3	0.10177	0.511112	0.50931	3	2.8
97SM4	Wsl	3.3	17.55	0.11358	0.511209	0.509198	0.8	2.9
Quartzofeldspathic orthogneiss, initial ratios calculated for 2.64 Ga								
03SM13	Wgn	4.78	28.92	0.09985	0.511029	0.509285	1.6	2.8
03SM33	Wgn	4.53	28.15	0.0973	0.511034	0.509335	2.6	2.8
Baggot Rocks granite, initial ratio calculated for 2.43 Ga								
97SM6	XBr	5.07	24.91	0.12309	0.511261	0.50929	–3.9	3.2

Note: T_{CR}, crustal residence age. Analytical details: ~100 mg of sample were dissolved in HF–HNO_3 then converted to chlorides in a Parr dissolution vessel. One-third of the sample was then spiked with ^{87}Rb, ^{84}Sr, ^{149}Sm, and ^{146}Nd. Cation-exchange procedures were used to separate Rb, Sr, and rare-earth elements. Sm and Nd were further separated in di-ethyl-hexyl orthophosphoric acid columns. Isotopic measurements were made on a VG Sector multi-collector mass spectrometer at the University of Wyoming, Laramie. An average ^{143}Nd/^{144}Nd ratio of 0.511850 ± 17 (2σ) was measured for the La Jolla Nd standard. Blanks for Sm and Nd are <17 pg; no blank corrections were made. Uncertainties in Nd and Sm concentrations of ±2% of the measured value. Uncertainties on initial $\varepsilon_{\mathrm{Nd}}$ are ±0.5. Nd crustal residence ages are calculated based upon the depleted mantle model of Goldstein et al. (1984).

[a] Sample dissolved on hot plate.

[b] Larger sample dissolved (0.3–0.5 g).

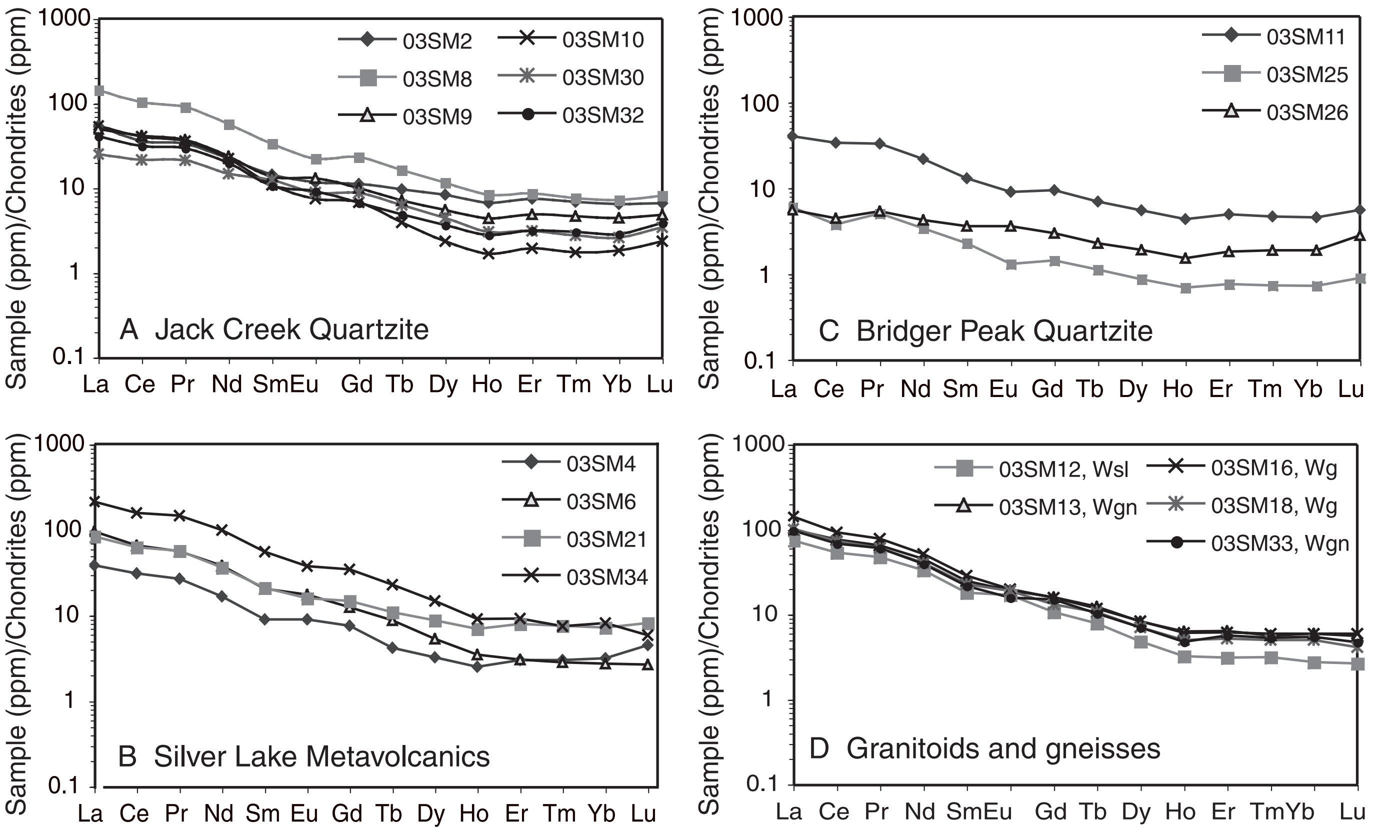
The FeO*/(FeO* + MgO) values for these rocks extend between 0.59 and 0.65. All samples are classified as magnesian and calc-alkalic to alkali-calcic according to B.R. Frost et al. (2001) (Figs. 5*a*, 5*b*). One sample from the quartzofeldspathic basement is strongly peraluminous but all other samples are metaluminous (Fig. 5*c*) (B.R. Frost et al. 2001). The high aluminum saturation index of 1.27 for sample 03SM33, as defined by Shand (1943), may reflect loss of alkalis as evidenced by the sericitization of the feldspars.

All Sierra Madre granitoids and gneisses have modest LREE enrichment ($La_n/Sm_n > 4$) and HREE depletion (Gd_n/Yb_n = 2.6–3.9) (Fig. 4*d*). Both slightly negative and slightly positive europium anomalies are found in these samples (Eu/Eu* = 0.9–1.2). The REE patterns of the granitoids and gneisses are indistinguishable from those of the Jack Creek quartzite and Silver Lake metavolcanics.

U–Pb geochronology

Two samples from Archean rocks of the Sierra Madre were selected for U–Pb zircon geochronology to better constrain the age and depositional history of the Phantom Lake metamorphic suite. Sample 03SM13 is a sample of quartzofeldspathic orthogneiss interpreted to be Archean basement of the Sierra Madre (Houston et al. 1992; Houston

Fig. 4. Rare-earth element (REE) patterns for Archean rocks of the Sierra Madre. (A) Jack Creek quartzite, (B) Silver Lake metavolcanics, (C) Bridger Peak quartzite (all are all members of the Phantom Lake metamorphic suite, and (D) granitoids and gneiss.



and Graff 1995). The other sample, 03SM6, a metadacite from the Silver Lake metavolcanics, was chosen to obtain direct information on the depositional age of the supracrustal units of the Phantom Lake metamorphic suite in the Sierra Madre.

Zircons in sample 03SM13 are pink to slightly brown, euhedral, doubly terminated crystals that vary in size from 150 μm × 275 μm to 165 μm × 325 μm. Cracks and inclusions are present in some grains within this sample. Eight of the clearest, inclusion-free crystals were selected and abraded between 1 and 4.5 h before dissolution and analysis by thermal ionization mass spectrometry (TIMS). Th/U ratios for these grains vary from 0.47 to 0.61, which are typical of igneous zircon (Th/U ≥ 0.5; Hoskin and Schaltegger 2003). ^{207}Pb/^{206}Pb ages range from 2618 to 2650 Ma, and individual analyses range from 13% to 30% discordant. No correlation exists between the length of time a crystal was abraded and the ^{207}Pb/^{206}Pb age or discordance of the analysis. The single-grain analyses are interpreted to indicate a late Archean crystallization age even though they plot in a non-linear array on a concordia diagram (Fig. 6*a*). Because no rims were observed on any of the crystals, and because metamorphic overgrowths are likely to be removed by abrasion, the scatter in the data may reflect the presence of a small inherited component in the zircon. For the purposes of interpreting the Nd isotopic data presented in this study, we adopt the ^{207}Pb/^{206}Pb date of the most concordant point, 2.64 Ga, as an estimate of the intrusive age of this late Archean orthogneiss.

The second sample selected for U–Pb zircon geochronology was 03SM6, a porphyritic metadacite from the Silver Lake metavolcanics. Zircons from this sample were clear, euhedral, and elongate, 80 μm × 300 μm in size. Five clear, inclusion-free zircons were abraded between 1 and 4.5 h prior to dissolution and TIMS analysis. Th/U ratios for these grains vary from 0.34 to 0.85. As with sample 03SM13, the data plot in a non-linear array on a concordia diagram (Fig. 6*b*) and the analyses range from 9% to 66% discordant. ^{207}Pb/^{206}Pb ages range from 2662 to 2699 Ma. We interpret the ^{207}Pb/^{206}Pb age of the least discordant point, 2.68 Ga, as an estimate of the crystallization age for the dacite. The elongate crystal morphology, the homogeneous population, and the Th/U are typical of magmatic zircon and not of metamorphic zircon, for which Th/U is typically <0.1 and often ~0.01 or lower (Hoskin and Schaltegger 2003). We note that even the crystal with the oldest Pb/Pb age is younger than the reported age of the Spring Lake granodiorite (2710 ± 10 Ma, Premo and Van Schmus 1989), which is interpreted to intrude the base of the Phantom Lake metamorphic suite.

Based on the ^{207}Pb/^{206}Pb dates determined for the quartzofeldspathic orthogneiss (sample 03SM13) of 2618–2650 Ma and the metadacite (sample 03SM6) of 2662–2699 Ma, it appears that the dated orthogneiss sample does not represent basement to the Phantom Lake metamorphic suite. The ^{207}Pb/^{206}Pb dates for sample 03SM13 are within the range of ages for voluminous granitic magmatism in the Wyoming Province in the Granite Mountains and the Wind River Range (Ludwig and Stuckless 1978; Langstaff 1995; Frost et

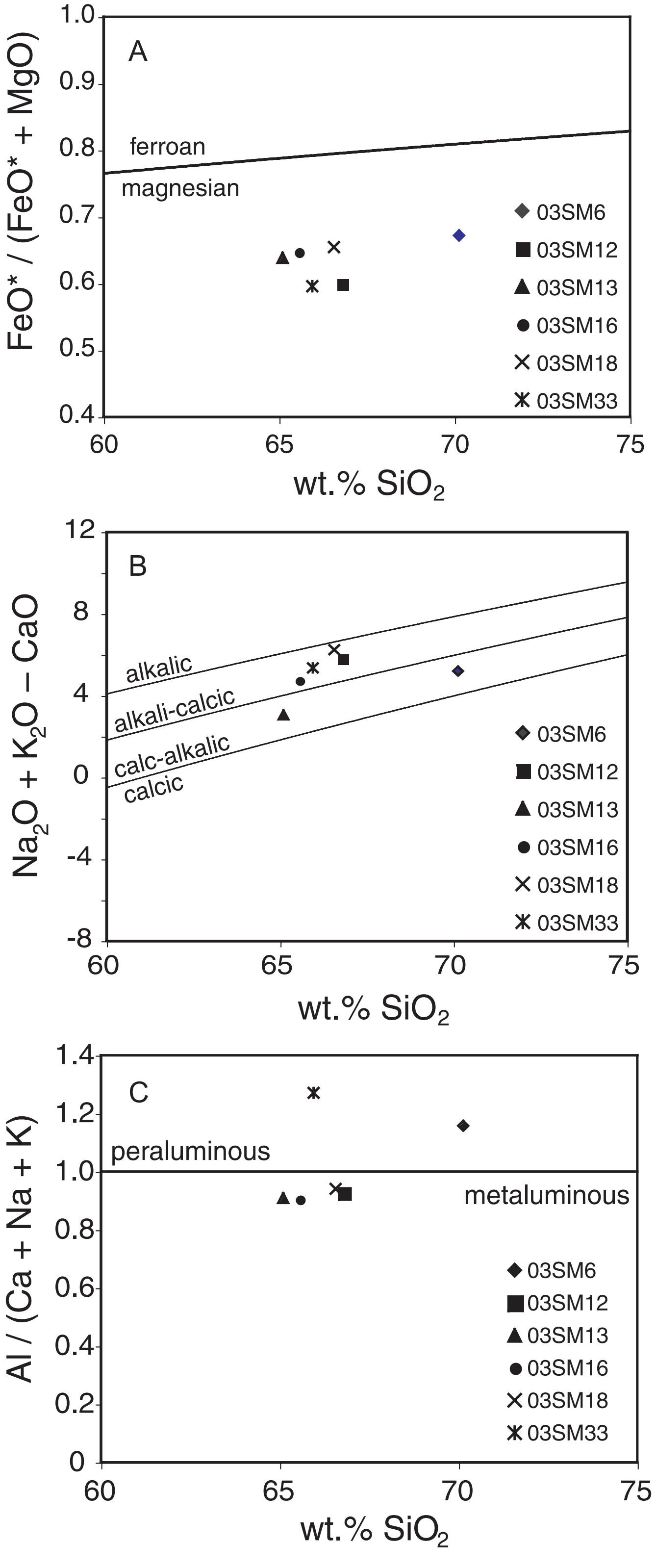


Fig. 5. Geochemical classification for metaigneous rocks of the Sierra Madre based on the classification scheme of B.R Frost et al. (2001).

al. 1998; Fruchey 2002; Wall 2004). Younger granites in this suite, such as the 2.63 Ga Louis Lake batholith, are mainly unfoliated (Frost et al. 1998). However, the older granites of the suite, including the Long Creek Mountain granite (2640 ± 20 Ma, Ludwig and Stuckless 1978) and the Circle Bar granite (2622–2650 Ma, Langstaff 1995; and ca. 2640 Ma, Fruchey 2002) are foliated, magnesian granites like the Sierra Madre orthogneiss.

Nd isotopic data

The Sm–Nd isotopic data is summarized in Table 3 for both the supracrustal units and the granitoids and gneisses of the Sierra Madre. 2.68 Ga was used for initial isotopic ratio calculations except for the Baggot Rocks granite that has a crystallization age of 2429 ± 4 Ma (Premo and Van Schmus 1989). 2.68 Ga was chosen because it is the only available age estimate from a unit within the Phantom Lake metamorphic suite. Nd model ages are based on the depleted mantle evolution model of Goldstein et al. (1984).

Jack Creek quartzite

Analyses of six samples are presented for the Jack Creek quartzite (Table 3). The ^{147}Sm/^{144}Nd ratio ranges from 0.0903 to 0.1180 plus one sample with 0.1557 and initial ε_{Nd} values vary from –0.2 to +4.3 (Fig. 7). The mainly positive initial ε_{Nd} values for the Jack Creek samples suggest that these sediments were derived from juvenile sources. The ^{147}Sm/^{144}Nd ratio for the Jack Creek samples is within the range of typical upper continental crust (0.095–0.125) except for sample 03SM30 (Fig. 7*c*). Sample 03SM30 is a coarse-grained arkose containing larger grains of sericitized feldspars with accessory grains of apatite and zircon. The ^{147}Sm/^{144}Nd ratio (0.153) is the highest value measured for the entire suite of samples. The ΣREE of sample 03SM30 is one of the lowest of all the supracrustal rocks owing to the high percentage of quartz in the rock (Table 1). Heavy minerals dominate the ΣREE in rocks chiefly composed of quartz (Cullers et al. 1979; Frost and Winston 1987), and the presence of both zircon and apatite could account for the high Sm/Nd ratio of quartz-rich sample 03SM30. Alternatively, the high Sm/Nd ratio could be due to input of a source with high Sm/Nd values.

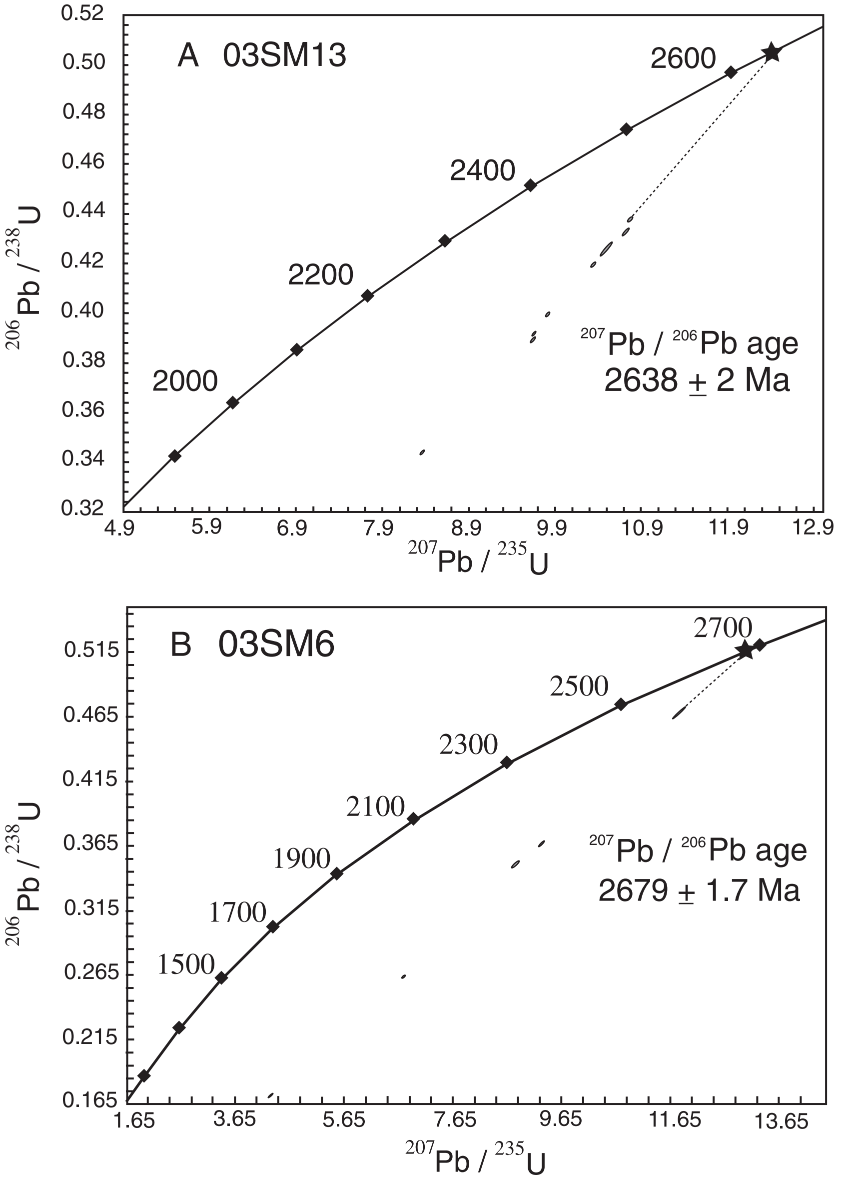
Silver Lake metavolcanics

A metadacite, two metapsammites, and a calcareous metasedimentary rock were analyzed from the Silver Lake metavolcanics. The Nd isotopic data for the Silver Lake metavolcanics were the least variable of all data for the supracrustal units (Fig. 7). The ^{147}Sm/^{144}Nd ratio (0.099–0.110) for all samples is within the range of the upper continental crust and the calculated crustal residence ages were all between 2.7 and 2.9 Ga (Figs. 7, 8). The uniform crustal residence ages suggest either a single source or well-homogenized source areas for the Silver Lake metavolcanic samples. The initial ε_{Nd} for these samples varies from 1.5 to 4.5 (Fig. 7*b*).

Bridger Peak quartzite

Three different quartzose metasedimentary rock samples were analyzed from the Bridger Peak quartzite: one arkose and two arenites. The initial ε_{Nd} (–2.5 to 2.9) and ^{147}Sm/^{144}Nd (0.108–0.152) make this the unit with the most variable Nd isotopic character (Fig. 7). The most extreme composition is

Fig. 6. (A) Concordia diagram for quartzofeldspathic orthogneiss, sample 03SM13. The $^{207}Pb/^{206}Pb$ age of the least discordant fraction, 2638 ± 2 Ma, is adopted as the best estimate for the intrusive age of this orthogneiss. (B) Concordia diagram for metadacite, sample 03SM6. $^{207}Pb/^{206}Pb$ age of the least discordant fraction, 2679 ± 2 Ma, is adopted as the best estimate for the extrusive age of this metadacite.



that of sample 03SM26; all other samples have $^{147}Sm/^{144}Nd$ comparable to upper continental crust and modern river sediments (Goldstein et al. 1984 and references therein). Sample 03SM26 has a higher Sm/Nd ratio and the most negative initial ε_{Nd} of the Bridger Peak samples. It is a coarse-grained quartz arenite with small amounts of microcline, muscovite, biotite, zircon, and apatite. Like sample 03SM30 from the Jack Creek quartzite, sample 03SM26 has one of the lowest ΣREE of all the supracrustal samples analyzed and therefore its Sm and Nd budget may be dominated by accessory minerals.

Granitoids and gneisses

All initial values for the granitoids and gneisses were calculated at 2.68 Ga, except for the samples from the Baggot Rocks granite, which will be discussed separately. This age was chosen for reduction to compare initial Nd isotopic compositions to the Phantom Lake metamorphic suite. The igneous ages of these gneisses are unknown except for sample 03SM13, which is ca. 2.64 Ga. If the quartzofeldspathic gneiss were age-corrected to 2.64 Ga, the initial ε_{Nd} would be 0.5 ε_{Nd} units more negative, a shift within the analytical uncertainty of ±0.5 ε_{Nd} units. For this reason we interpret the initial Nd isotope values at 2.68 Ga, confident that these interpretations would be unchanged even if the true crystallization age of the gneisses were some 40 Ma older or younger than 2.68 Ga.

The Nd isotopic composition for the granitoids and gneisses

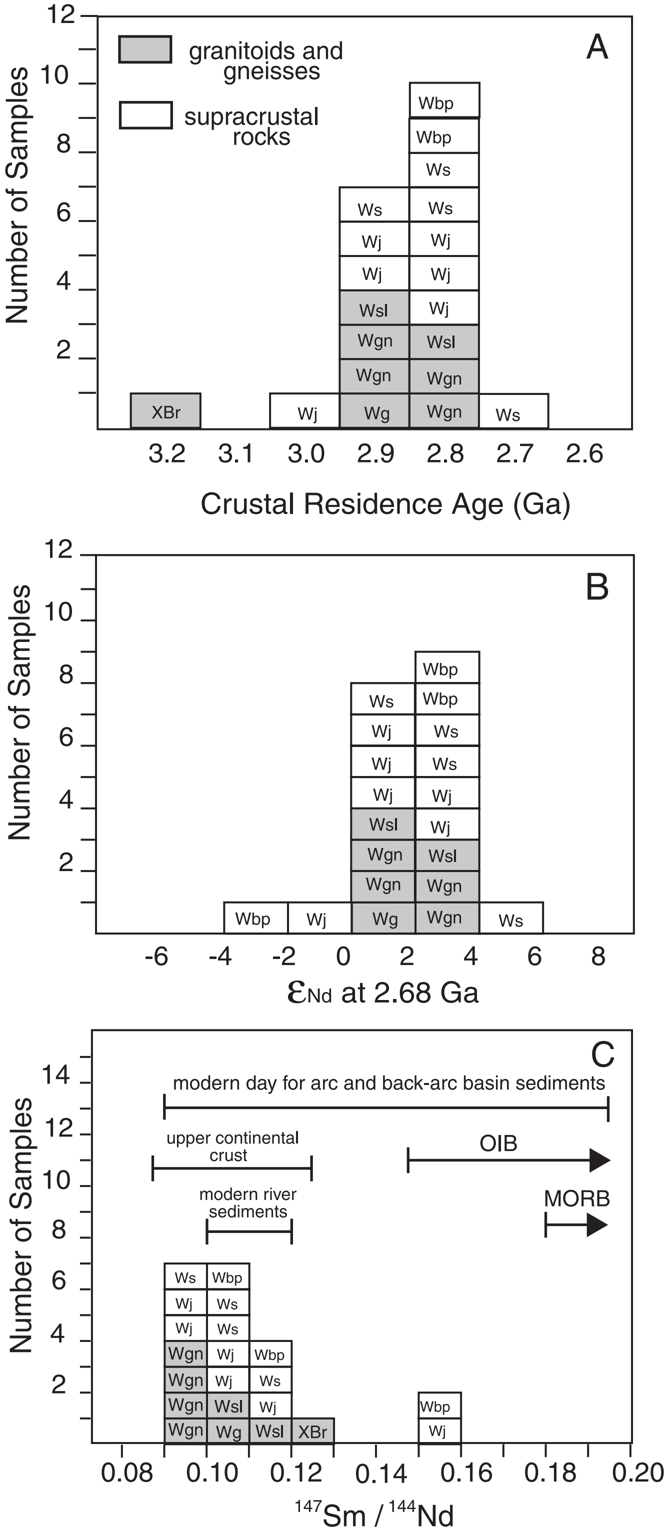


Fig. 7. (A) Histogram of crustal residence ages for rocks of the Sierra Madre based on the depleted mantle model of Goldstein et al. (1984). The crustal residence ages for samples 03SM26 and 03SM30 were not calculated owing to their high ^{147}Sm/^{144}Nd ratios. The crustal residence age of the Baggot Rocks granite is included in this plot (3.2 Ga). (B) Histogram of initial ε_{Nd} values. Sample 97SM6 from the Baggot Rocks granite is not represented on the ε_{Nd} histogram because it has a crystallization age of 2429 Ma (Premo and Van Schmus 1989). (C) Histogram of ^{147}Sm/^{144}Nd ratio for Sierra Madre supracrustal rocks and metaigneous rocks. Values for modern day basin sediments, upper continental crust, modern river sediments, ocean-island basalt (OIB), and mid-ocean ridge basalt (MORB) from Goldstein et al. (1984), McLennan et al. (1990), and references therein.

are all relatively uniform with ^{147}Sm/^{144}Nd from 0.092 to 0.114, initial ε_{Nd} from 0.8 to 3.1, and crustal residence ages from 2.8 to 2.9 Ga (Fig. 7). The overlapping Nd isotopic compositions of the granitoids and gneisses and the Phantom Lake metamorphic suite suggest that the gneissic rocks could be a source(s) for the metasedimentary rocks. Both the gneisses and the Phantom Lake suite also have similar REE patterns, providing further evidence that the gneisses could be the source of the metasedimentary rocks. All of the granitoids and gneisses contain a significant amount of juvenile crustal material, as evidenced by their positive ε_{Nd} values. As such, they can be considered additions to the mass of the Wyoming Province.

The Baggot Rocks granite is the youngest intrusive sample evaluated. All initial values for Baggot Rocks samples have been calculated at 2.43 Ga, based on the reported U–Pb crystallization age of Premo and Van Schmus (1989). The ^{147}Sm/^{144}Nd value of 0.1231 is typical for continental crust (Fig. 7*c*). An initial ε_{Nd} of –3.9 indicates that the Baggot Rocks granite assimilated the largest proportion of Archean crust of any sample studied (Fig. 7*b*). Sample 97SM6 has a depleted mantle crustal residence age of 3.2 Ga, which is older than any other sample analyzed (Fig. 7*a*). Bennett and DePaolo (1987) reported a negative initial ε_{Nd} of –8.1 for another sample of the Baggot Rocks granite, which is even less radiogenic than the value from this study.

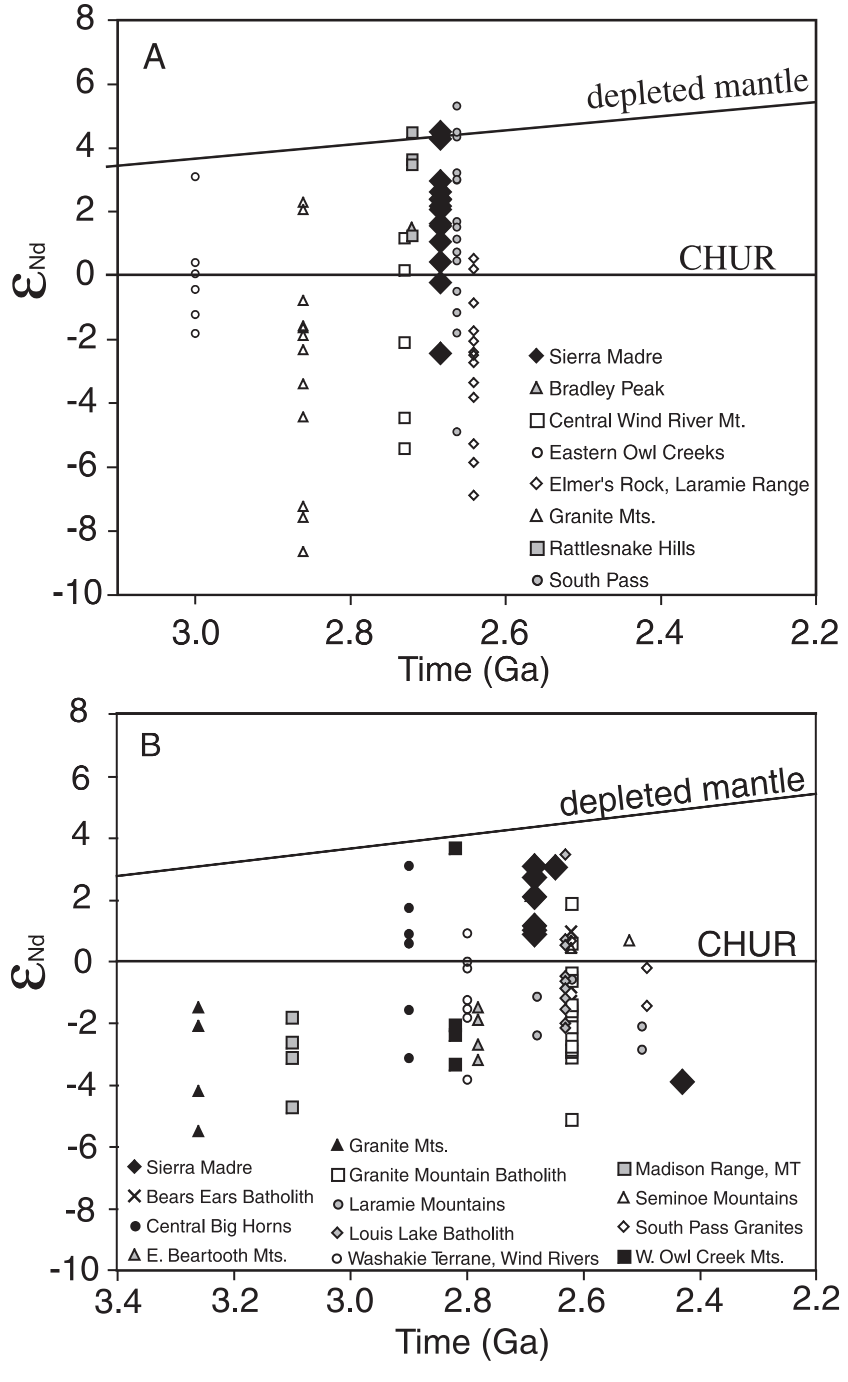
Discussion

Re-evaluation of the Phantom Lake metamorphic suite stratigraphy

Each of the three units that compose the Phantom Lake metamorphic suite include volcanogenic, volcaniclastic, and coarse clastic sediments, although in different proportions. For example, the prevalence of mafic metavolcanic rocks distinguishes the Silver Lake metavolcanics from the quartzite-dominated units in the Phantom Lake metamorphic suite. Nonetheless, the clastic metasedimentary rocks from the Silver Lake metavolcanics have REE patterns that are indistinguishable from those of the fine-grained clastic metasedimentary samples from the two quartzite-dominated units, the Bridger Peak quartzite and the Jack Creek quartzite.

Both the Bridger Peak quartzite and the Jack Creek quartzite are composed of abundant quartzite with minor amounts of phyllite, metacarbonate, and pebble conglomerate. The main difference between the two units is the presence of the Deep Gulch Conglomerate Member at the base of the Jack Creek quartzite, although this conglomerate is not present at all Jack Creek exposures. Aside from the presence of the Deep Gulch Member, these two quartzites are indistinguishable from each other in the field, petrographically, and geochemically. For example, modal compositions of quartzite samples from both the Jack Creek quartzite and the Bridger

Fig. 8. Comparison of initial ε_{Nd} values of (A) supracrustal rocks and (B) gneisses and granitoids of the Sierra Madre to other Archean supracrustal rocks and gneisses and granitoids found within Wyoming Province (Frost et al. 1998, 2006*b*; Mueller et al. 1993; Wooden and Mueller 1988; Patel et al. 1999; Fruchey 2002; Kirkwood 2000; Kruckenberg et al. 2001; Wall 2004). CHUR, condritic uniform reservoir.



Peak quartzite are comparable. The quartz–feldspar–mafic (QFM) mean for each sample set is Q = 67, F = 14, and M = 19 for the Jack Creek quartzite and Q = 69, F = 13, and M = 18 for the Bridger Peak quartzite (Karlstrom et al. 1981; Houston et al. 1993). Furthermore, the REE patterns for both fine- and coarse-grained samples from the Jack Creek quartzite and Bridger Peak quartzite all have the same general pattern of LREE enrichment and relatively flat HREE (Figs. 4*a*, 4*c*). The only distinct REE patterns are for the two Bridger Peak quartzite samples (03SM25, 03SM26) with the highest SiO_2, which have lower ΣREE and flatter patterns than the other quartzite samples (Table 1).

The Jack Creek quartzite, Silver Lake metavolcanics, and Bridger Peak quartzite all have been subjected to multiphase deformation that has obscured stratigraphic relationships. Further difficulty in deciphering the stratigraphy of the Phantom Lake metamorphic suite includes ambiguous top and bottom criteria, poor preservation, and lack of marker horizons. Dividing the Phantom Lake metamorphic suite into three separate units allows for easy correlation with the Phantom Lake metamorphic suite of the Medicine Bow Mountains, and this is apparently the basis for the original definition of the three units. However, we suggest that it is possible that the Jack Creek quartzite and the Bridger Peak quartzite could be the same geologic unit based on field observations, and the petrographic, geochemical, and isotopic evidence presented in this study.

Provenance of the Phantom Lake metamorphic suite

The Phantom Lake metamorphic suite has geochemical and isotopic characteristics analogous to modern arc assemblages. The dominant mafic volcanic and volcaniclastic rocks with sparse dacites, quartzites, pelites, semi-pelites, and metacarbonate rocks that make up the Silver Lake metavolcanics are analogous to lithologies typically found in back-arc basins of intra-oceanic island-arc settings (Marsaglia 1995; Hawkins 2003). More problematic is the high SiO_2 content of the quartzites of the Phantom Lake metamorphic suite, which is not common in modern island arcs. Rocks with such mineralogical maturity are typically associated with old continental crust, a provenance dominated by recycled quartz-rich sediments or a quartz-rich granite (McLennan et al. 1993), although Van Wyck and Norman (2004) present evidence that first-cycle, quartz-rich sediments can be deposited in tectonically active environments. Quartz-rich lithologies are common in Archean depositional environments, and the origin of these massive sands remains a major problem in Archean geology (McLennan and Taylor 1984; Eriksson et al. 1998).

Sample 03SM6 is the only volcanic sample analyzed in this investigation. This metadacite from the Silver Lake metavolcanics has a positive initial Nd isotopic signature of ε_{Nd} = 2.4, requiring derivation from a juvenile source. The $^{147}Sm/^{144}Nd$ ratio for the sample is within range for the upper continental crust as well as sediments from back-arc and fore-arc basins (Fig. 7*c*). The LREE-enriched, flat HREE pattern of the metadacite shows no resemblance to the relatively flat mid-ocean ridge basalt pattern or the LREE-depleted signature of oceanic plateau rocks, but rather is similar to the REE pattern of island-arc volcanics.

With the exception of one sample from the Bridger Peak quartzite with initial ε_{Nd} of –2.5, all supracrustal rock samples from the Phantom Lake metamorphic suite preserve evidence of derivation from relatively juvenile crust or depleted mantle-derived sources (Figs. 7, 8). The fine-grained samples have ε_{Nd} values of 0.4–4.5. The $^{147}Sm/^{144}Nd$ ratio for these samples is typical of upper continental crust and volcanic-arc rocks (Goldstein et al. 1984). REE patterns for the fine-grained samples of the Phantom Lake metamorphic suite are LREE enriched, have little to no Eu-anomaly, and display flat HREE patterns. This REE pattern is similar to those of modern day fore-arc and back-arc basin sediments (McLennan et al. 1990). Based on the REE patterns and radiogenic Nd isotope values, we suggest that an active tectonic setting, such as a fore-arc or back-arc basin, may have been the depositional environment for these sediments.

The coarse-grained samples from the Phantom Lake metamorphic suite are less radiogenic and have more variable Nd isotopic values than the fine-grained samples, yet the crustal residence ages for these samples all lie between 2.8 and 2.9 Ga (Fig. 7*a*). Two samples with higher $^{147}Sm/^{144}Nd$ ratios are probably the result of Sm/Nd enrichment owing to the presence of accessory minerals such as zircon, apatite, and monazite in SiO_2-rich rocks. REE patterns and $^{147}Sm/^{144}Nd$ ratios for the other coarse-grained samples of the Phantom Lake metamorphic suite are similar to both REE patterns for the fine-grained Phantom Lake samples and modern-day fore-arc and back-arc basins (McLennan et al. 1990). A similar oceanic arc setting is indicated for these samples, although some detritus from older continental crust seems to be required in samples 03SM26 and 03SM30 that have less radiogenic initial ε_{Nd} values of –2.5 and –0.2.

It is possible that the granitoids and gneisses similar to those analyzed in this study are the source of the sediments for the Phantom Lake metamorphic suite. The granitoids and gneisses have similar Nd isotopic values and REE patterns to those of the supracrustal units of the Phantom Lake metamorphic suite (Figs. 4, 7). The Deep Gulch Conglomerate Member of the Jack Creek quartzite contains clasts of quartzofeldspathic gneiss and feldspars interpreted as derived from the underlying gneiss unit. However, the 2647 Ma quartzofeldspathic gneiss dated as part of this investigation indicates that not all orthogneisses are basement to the Phantom Lake metamorphic suite. Instead, this gneiss represents an additional magmatic event in the Sierra Madre ca. 2645 Ma. The Bennett Peak orthogneiss further southeast in the Sierra Madre may also be a part of a 2.64 Ga intrusive event; although four zircon fractions analyzed by Harper (1997) yielded $^{207}Pb/^{206}Pb$ ages from 2571 to 2620 Ma, a chord through two of these fractions has an upper intercept age of ca. 2640 Ma.

The depositional environment of the Phantom Lake metamorphic suite has been an enduring question in large part because the lithologic assemblage of this supracrustal succession does not uniquely identify a depositional environment. In particular, the large proportion of high-silica quartzite led early workers to propose a fluvial depositional environment for the Phantom Lake metamorphic suite even though Archean successions in a variety of depositional environments commonly include quartzites (Eriksson et al. 1998). Our Nd isotope data in particular requires that the source for the clastic detrital rocks and the dacite are isotopically juvenile. This precludes derivation from the Archean Wyoming Province or any other ancient craton. Instead, we suggest a depocenter adjacent to an oceanic arc as the depositional environment for the Phantom Lake metamorphic suite.

Relationship of the Sierra Madre to the Wyoming Province

Late Archean pelitic rocks from the central and northern Wyoming Province typically have negative ε_{Nd} values (e.g., Frost 1993) (Fig. 8*a*). These data were interpreted to suggest that the Wyoming Province is composed of early to middle Archean age crust, and that this crust was exposed and eroded to produce the supracrustal sequences. In striking contrast, this study has shown that the ε_{Nd} values for the Sierra Madre are among the most positive in the Wyoming Province. Only a few other supracrustal belts in the southern Wyoming Province, including the ca. 2.68 Ga South Pass greywackes, the ca. 2.72 Ga supracrustal rocks from the Rattlesnake

Hills, and the ca. 2.72 Ga greenstone succession from Bradley Peak have similarly positive ε_{Nd} values (Frost et al. 2006*b*) (Fig. 8*a*).

Like most supracrustal successions in the central and northern Wyoming Province, most plutons from the Beartooth, Bighorn, Granite, and Owl Creek mountains, and Wind River and Madison ranges have negative initial ε_{Nd} values, which requires the involvement of ancient continental crust in their petrogenesis (Wooden and Mueller 1988; Mueller et al. 1996; Frost et al. 1998; Kirkwood 2000; Kruckenberg et al. 2001; Fruchey 2002) (Fig. 8*b*). The sparse, more radiogenic ε_{Nd} values from these localities tend to be from tonalitic samples. In contrast, gneisses and granitoids from the Sierra Madre have uniformly positive initial ε_{Nd}, and have some of the youngest Nd model ages in the Wyoming Province (Fig. 8*b*). Only the much younger Baggot Rocks granite has an unradiogenic initial Nd isotopic composition. Until the intrusion of this granite at ca. 2.43 Ga, there is no evidence for the assimilation of ancient continental crust in the Sierra Madre, and all older granitoids and gneisses represent juvenile additions to the continental crust.

The supracrustal rocks at South Pass are similar in age and Nd isotopic character to the Phantom Lake metamorphic suite of the Sierra Madre (e.g., Condie 1967; Hausel 1991; Steenhoek et al. 1995; C.D. Frost et al. 2001; Frost et al. 2006*b*). Andesite from the youngest part of the succession yielded a U–Pb zircon age of 2671 ± 4 Ma, which constrains the depositional age of enclosing graywackes (Frost et al. 2006*b*). This age is close to the estimated crystallization age of the dacite from the Silver Lake metavolcanics in the Phantom Lake metamorphic suite of ca. 2.68 Ga. The supracrustal units of both South Pass and the Sierra Madre have juvenile Nd isotopic signatures suggesting that both sequences were derived from young, mantle-derived crust with little continental input (Fig. 8*a*). The lower units of the South Pass sequence have lower ε_{Nd} values than the upper units of this sequence such as the Miners Delight Formation. It is interpreted that the older units are deposits from a continental margin or back-arc setting and the youngest unit is derived from a juvenile island-arc source (Frost et al. 2006*b*).

The deformation histories of the supracrustal sequences from the Sierra Madre and South Pass are also similar. Both sequences of rocks have been metamorphosed to amphibolite facies. The structure of both areas is interpreted to be a synclinorium affected by at least two deformational events. The first event produced the tight isoclinal folds seen within the supracrustal units; this was followed by a second, less intense compressional event producing more open folds and refolding the previous isoclinal folds (Graff 1978; Hausel 1991; Houston et al. 1992).

Two other supracrustal successions from the Wyoming Province with juvenile Nd isotopic compositions are older than the Phantom Lake metamorphic suite and instead may be coeval with the underlying Vulcan Mountain metavolcanics: those at Bradley Peak in the Seminoe Mountains (Klein 1982) and the Rattlesnake Hills terrane in the northern Granite Mountains (Fruchey 2002). The ca. 2.72 Ga Bradley Peak succession is composed of >5000 m of basalt and komatiitic ultramafic rocks with lesser amounts of iron formation, fine-grained siliceous and aluminous metasedimentary rocks, and minor felsic volcanic rocks (S. Goldich, reported in Houston et al. 1993; Blackstone and Hausel 1991). The 2.72 Ga Rattlesnake Hills supracrustal sequence is composed of ~ 150 m of metabasalt with minor felsic tuff conformably overlain by ~3500 m of metagraywacke and minor metavolcanic rocks (Houston et al. 1993; Fruchey 2002). Although it is possible that these three supracrustal sequences represent three independent depocenters, the overwhelming proportion of mafic rocks in each of these three exposures and the positive initial ε_{Nd} values of both the Rattlesnake Hills and Bradley Peak lead us to suggest that these rocks could be part of a single supracrustal succession located to the south of the Wyoming Province ca. 2.71 Ga.

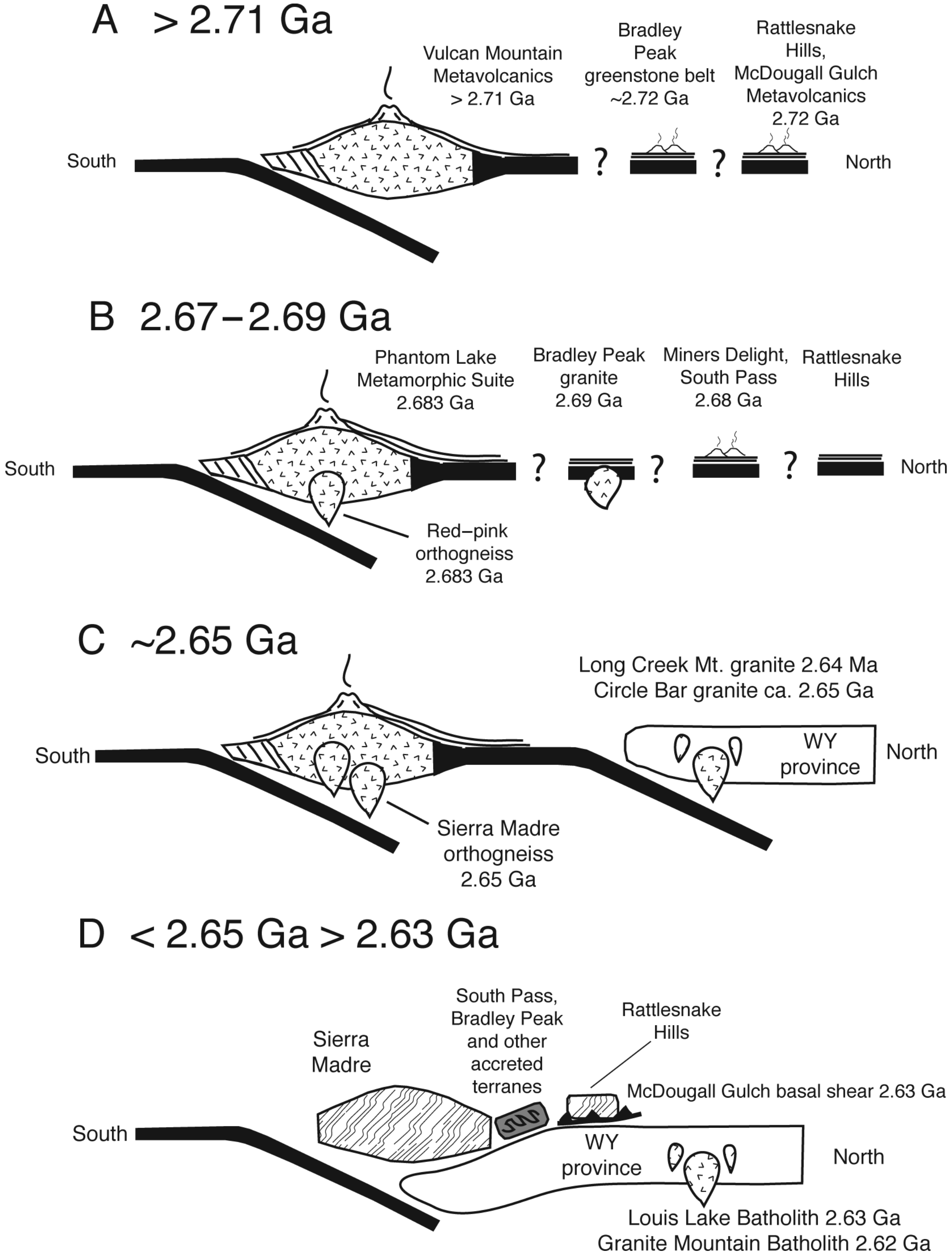
In addition to synchronous deposition of supracrustal rocks in the Sierra Madre and elsewhere in the Wyoming Province, granitic magmatism also took place simultaneously in both places. Three distinct pulses of granitic magmatism (2.72–2.67, 2.65–2.60, 2.55–2.50 Ga) have been documented in the Wyoming Province. The two older pulses are related to a long-lived active margin along the south and southwest borders of the Wyoming Province (Frost et al. 1998; Chamberlain et al. 2003). In the Sierra Madre, the oldest pulse is represented by the 2.71 Ga Spring Lake granodiorite and the 2.68 Ga red–pink orthogneiss (Premo and Van Schmus 1989), and the middle pulse is represented in the Sierra Madre by the ca. 2.64 Ga orthogneiss.

Evolution of the Sierra Madre and accretion to the Wyoming Province

Because the Vulcan Mountain metavolcanics are interpreted to be intruded by the Spring Lake granodiorite at 2710 ± 10 Ma, the Vulcan Mountain metavolcanics and the quartzofeldspathic basement gneisses are interpreted to have formed prior to ca. 2.71 Ga (Premo and Van Schmus 1989; Houston et al. 1992). The Vulcan Mountain metavolcanics are assumed to lie unconformably above the basement, but the contact between these two units has been obscured by subsequent deformation (Houston and Graff 1995) (Fig. 9*a*). No older radiometric dates have been obtained for rocks from the Sierra Madre; therefore, we have no minimum age estimate for either the quartzofeldspathic gneiss or the Vulcan Mountain metavolcanics. However, ε_{Nd} at 2.68 Ga for the gneisses are near estimates of contemporary depleted mantle. It is, therefore, unlikely that the basement gneiss can predate the Spring Lake granodiorite by >100 million years or else its initial ε_{Nd} would be unrealistically high, even for wholly depleted mantle-derived magmas.

Deposition of the Phantom Lake metamorphic suite continued through ca. 2.68 Ga as indicated by U–Pb zircon data from an interbedded dacite layer in the Silver Lake metavolcanics (this study). Metamorphic titanite growth in the Vulcan Mountain metavolcanics at 2.69 Ga was interpreted as the time of a regional metamorphic event by Harper (1997). Both the extrusion age of the dacite and the titanite age overlap within error of the intrusion age of the red–pink orthogneiss (2683 ± 6 Ma) (Premo and Van Schmus 1989). Also, at approximately ~2.69 Ga the Bradley Peak granite intruded the greenstone succession in the Seminoe Mountains (Wall 2004). There was also volcanic activity at South Pass as documented by the ca. 2.67 Ga andesite (Frost et al. 2006*b*)

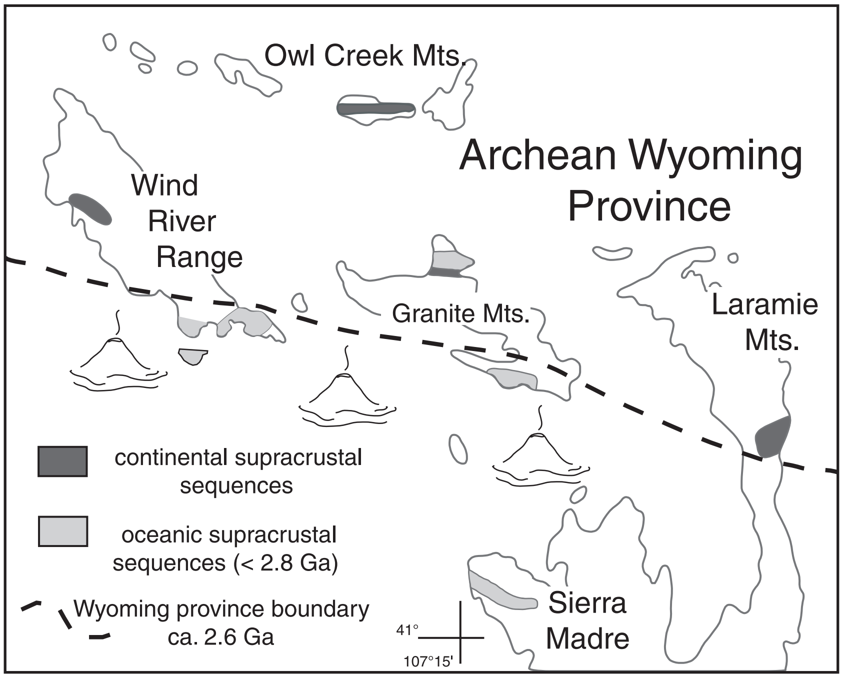
Fig. 9. Inferred tectonic settings for Archean rocks of the Sierra Madre and adjacent parts of the southern Wyoming Province. (A) Deposition of the Vulcan Mountain metavolcanics, Bradley Peak greenstone, and the McDougall Gulch metavolcanics ca. 2.71–2.72 Ga, possibly as a single arc complex. (B) Intrusions in the Sierra Madre and at Bradley Peak coinciding with deposition of the Phantom Lake metamorphic suite and the Miners Delight Formation at South Pass ca. 2.67–2.69 Ga. (C) Ca. 2.65 Ga plutonism in both the Granite Mountains and the Sierra Madre. (D) Tectonic shortening within the oceanic arc setting and obduction of the Rattlesnake Hills terrane onto the Wyoming (WY) craton ca. 2.65–2.63 Ga. This coincides with plutonism in both the Granite Mountains and the Wind River Range.



(Fig. 9*b*). Because of the greater proportion of quartz-rich clastic rocks and the presence of conglomeratic units within the Phantom Lake metamorphic suite, we interpret this sequence as deposited closer to a deeply eroded arc complex rather than the supracrustal sequences at Bradley Peak, South Pass, and the Rattlesnake Hills.

Granitic magmatism affected rocks in both the Sierra Madre and farther north in the Wyoming Province ca. 2.65 Ga

Fig. 10. Schematic representation of the southern margin of the Wyoming Province at ca. 2.6 Ga. Oceanic supracrustal sequences include rocks deposited at 2.72–2.65 Ga. They were accreted to the Wyoming Province prior to the intrusion of unfoliated 2.63–2.62 Ga granitoids exposed in the Wind River Range, Granite Mountains, Laramie Mountains, and Owl Creek Mountains (Frost et al. 1997, 1998; Verts et al. 1996; Wall 2004).



(Fig. 9*c*). Although the ca. 2.65 Ga magmatism in each of these areas is interpreted as arc-related, the magmas from the Sierra Madre are characterized by juvenile Nd isotopic signatures, whereas granites from the Wyoming Province have more evolved Nd isotopic character (Fig. 8*b*). We suggest that these arcs are contemporary with the Sierra Madre arc but that the latter was located farther south of the Wyoming Province away from the influence of continental crust. This ca. 2.65 Ga magmatic event was followed by voluminous intrusion of post-tectonic granites, including the 2630 ± 2 Ma Louis Lake batholith in the Wind River Range and the ca. 2620 Ma Granite Mountain batholith (Wall 2004).

Unlike any other rock in the Sierra Madre, the ca. 2.43 Ga Baggot Rocks granite has negative ε_{Nd} values (–8, –4) (Bennett and DePaolo 1987; this study). We suggest that this negative ε_{Nd} signature derives from incorporation of Wyoming Province crustal sources into the Baggot Rocks magma, and therefore the accretion of the Sierra Madre to the Wyoming Province predates the intrusion of the Baggot Rocks granite. On the other hand, collision and extreme deformation of the rocks of the Sierra Madre must postdate ca. 2.65 Ga, the minimum crystallization age for the foliated quartzofeldspathic gneiss dated as part of this study. This deformation event could have been a part of a ca. 2.63 Ga collision which docked the rocks of the Sierra Madre onto the southern continental margin of the Archean Wyoming Province while thrusting the Rattlesnake Hills terrane farther north (Fruchey 2002) (Fig. 9*d*). South-dipping reflectors north of the Cheyenne belt in the Sierra Madre have been interpreted by Morozova et al. (2002) to be Archean thrusts. These structural features could be evidence of the accretion of the Sierra Madre onto the Wyoming craton.

Conclusions

The Phantom Lake metamorphic suite was deposited in an intra-oceanic arc basin between 2.71 and 2.68 Ga and subsequently accreted onto the Wyoming Province sometime between 2.65 and 2.63 Ga. Prior to accretion, we envision the southern margin of the Wyoming Province as a series of arc-trench systems with relative motion towards the north, a tectonic setting comparable to the modern-day western Pacific region (Fig. 10). Based on the presence of voluminous mafic volcanic rocks and coeval magmatic activity, all with radiogenic ε_{Nd} values, we propose that the Vulcan Mountain metavolcanics of the Sierra Madre, the Bradley Peak greenstone belt, and the supracrustal sequence in the Rattlesnake Hills to be part of a depositional system beyond the influence of continental detritus from the Wyoming Province. Although the Sierra Madre represents an exotic block accreted onto the southern margin of the Wyoming Province as proposed by Chamberlain et al. (2003), it is no more exotic than the supracrustal sequences at South Pass, the Rattlesnake Hills, and Bradley Peak. The ca. 2.68 Ga date of a dacite from the Silver Lake metavolcanics and the Nd isotopic character of the Phantom Lake metamorphic suite are comparable to the ca. 2.67 Ga South Pass supracrustal sequence.

For these reasons, we propose that the rocks of the Sierra Madre are part of a relatively large, juvenile, composite terrane accreted onto the southern margin of the Archean Wyoming Province after 2.65 Ga. This accreted terrane demonstrates that lateral growth of continental crust occurred at cratonic margins during late Archean time. This type of tectonic regime has also been described for the Archean Superior

Province where rapid addition of juvenile terranes characterizes growth from 2.7 to 2.8 Ga (Card 1990; Percival et al. 1994; Puchtel et al. 1998; Polat and Kerrich 2001). Although it is thought that much of the Wyoming Province formed prior to 2.8 Ga (Wooden and Mueller 1988; Frost 1993) and subsequent growth and reworking took place primarily through magmatic addition (Frost et al. 1998), this study documents that lateral accretion was also an important tectonic process for the Wyoming Province in late Archean time.

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