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Petrogenetic and Tectonic Interpretation of Strongly Peraluminous Granitic Rocks and their Significance in the Archean Rock Record

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Abstract

Strongly peraluminous granitic rocks (SPG), defined by an aluminum saturation index greater than 1.1, become abundant in the rock record in the Neoarchean. This study identifies three different varieties of Neoarchean SPG in the Archean Wyoming Province, USA. These include calcic SPG, represented by the Webb Canyon Gneiss and Bitch Creek Gneiss of the Teton Range; calc-alkalic to alkali calcic suites composed entirely of SPG, including the Rocky Ridge garnet granite gneiss of the northern Laramie Mountains and the Bear Mountain granite in the Black Hills; and calc-alkalic to alkali-calcic suites that include both weakly and strongly peraluminous granitic rocks, such as the Mount Owen batholith, Wyoming batholith, and Bears Ears intrusion. Although the petrogenesis of all the SPG suites involves partial melting of crustal sources, the composition of those sources, the melting conditions, and the tectonic settings vary. The calcic suites originate by dehydration melting or water excess melting of hornblende-plagioclase rocks at relatively high temperature. The suites composed entirely of SPG form by partial melting of metasedimentary rocks by reactions involving muscovite at lower temperatures. Suites with both weakly and strongly peraluminous granite may form by partial

melting of metasedimentary rocks by reactions involving biotite, or by assimilation of aluminous melts of felsic crust by differentiated calc-alkalic magma. Most of the Wyoming SPG appear to have formed in collisional orogens, but SPG of the Wyoming batholith and Bears Ears granite are associated with continental arc magmatism. The appearance of SPG in the Neoarchean rock record marks the time when subduction enabled the formation of strong, thick, increasingly felsic continental crust, which in turn allowed development of a mature, clastic sedimentary cover. Lateral movement of crustal blocks led to collisional orogeny, SPG magma genesis, and the formation of the first supercontinents.

Introduction

Peraluminous rocks contain more Al than can be accommodated in feldspars alone (Shand, 1947). Shand defined the aluminum saturation index (ASI) as the molecular ratio $Al_2O_3/(CaO + Na_2O + K_2O)$. ASI will be 1.0 for any combination of plagioclase and alkali feldspars because alkali feldspars have 1 mole of Al and 1 mole of Na and/or K and anorthite has 2 moles of Al for 1 mole of Ca. The calculation of ASI commonly includes a correction for the presence of calcium in apatite, assuming all phosphorus in the rock is in apatite. The expression for ASI, including this correction, is:

$$ASI = (\text{wt. \% } Al_2O_3/101.94) / (\text{wt. \% } CaO/56.08 – 3.33 * \text{wt. \% } P_2O_5/141.95 + \text{wt. \% } Na_2O/61.982 + \text{wt. \% } K_2O/94.2)$$[1]

where the denominators are molecular weights of the respective oxides.

[1] Note that the coefficient for the phosphorus correction was incorrectly reported as 1.67 rather than 3.33 in Frost et al. (2001) and Frost and Frost (2008).

The aluminum saturation index differentiates peraluminous rocks, with ASI >1.0, from metaluminous rocks, with ASI < 1.0. Peraluminous rocks may be further subdivided into weakly peraluminous (1 < ASI < 1.1) and strongly peraluminous varieties (ASI ≥ 1.1) (Bucholz and Spencer, 2019; Sylvester, 1998).

Because peraluminous rocks have more molecular Al_2O_3 than can be accommodated in feldspars alone, one or more other aluminous phases must be present. For weakly peraluminous rocks, this phase may be aluminous biotite, but for strongly peraluminous rocks the phases can include muscovite, cordierite, garnet, tourmaline, topaz, spinel, corundum or an Al_2SiO_5 polymorph. The aluminous phases may be of magmatic origin, or may be entrained peritectic, restitic, or inherited crystals.

Strongly peraluminous granitic rocks (SPG) are commonly interpreted to derive from sedimentary sources (Chappell and White, 2001). Fine-grained clastic sedimentary rocks are aluminous as a result of removal of elements including Na and Ca during weathering and the formation of clays. Metamorphism and partial melting of such aluminous sources produce granite with peraluminous compositions (Nabelek, 2020). Strongly peraluminous granitic rocks formed by partial melting of metasedimentary rocks are potential monitors of source rock composition and temperature of partial melting (Bucholz and Spencer, 2019; Sylvester, 1998). However, to identify the source characteristics of strongly peraluminous granitic rocks, it is also necessary to take into account the specific melting reactions involved and the effect of subsequent magmatic processes, including flow segregation, assimilation, fractionation, and hydrothermal alteration (Clarke, 2019). Mayne et al. (2020) developed models to accommodate the changing bulk source composition during progressive melting and sequential segregation of partial melts from metapelitic rocks to reconstruct more accurately the composition of the source.

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Although most studies focus on SPG that are derived from metasedimentary crust, especially metapelitic rocks, other sources and mechanisms for the production of SPG are also possible including anatexis of mafic rocks, partial melting of quartzofeldspathic rocks, fractionation of low ASI minerals from a differentiating magma, and vapor phase removal of alkalies (Miller, 1985). Clarke (2019) identified additional processes for the formation of SPG, including diatexis of a metasedimentary rock followed by partial to complete removal of the restite, and contamination of a less aluminous magma by peraluminous metasedimentary rocks.

Well-studied Phanerozoic SPG intrusions occur primarily within collisional orogens (Nabelek, 2020; Sylvester, 1998). Emplacement of SPG typically post-dates metamorphism (Nabelek, 2020). In other tectonic environments, including continental arcs and extensional environments, small proportions of granite with ASI $\geq$ 1.1 may be present as components of intrusions with a range of silica and ASI (e.g., Brown et al., 2018; Stoeser and Frost, 2006).

Strongly peraluminous granitic rocks first become abundant in the Neoarchean (Bucholz and Spencer, 2019; Laurent et al., 2014). Neoarchean rocks of the Wyoming Province include a number of intrusive suites composed either entirely of SPG or that contain a prominent SPG component. The purpose of this paper is to examine these Neoarchean SPG occurrences to establish the characteristics of Archean SPG within a single craton, and to determine the sources and processes that formed them. This information helps to establish whether the full range of modern SPG-forming processes were operating as early as the Neoarchean, and has implications for the evolution of Earth's tectonic processes.

Neoarchean SPG of the Wyoming Province

The Wyoming Province is a block of Archean crust with origins that extend back to the Hadean (Frost et al., 2017; Mueller and Wooden, 2012). Neoarchean SPG occur across the Wyoming Province, from the Teton Range in the west to the Black Hills in the east (Fig. 1). This paper focuses on six Neoarchean intrusive granitic suites with significant proportions of SPG that have been sufficiently well-studied that the geologic context, and petrologic and geochemical character can be reasonably well-described. Three of the SPG-bearing suites are exposed in the Teton Range: the 2.68 Ga Webb Canyon gneiss, the 2.68 Ga Bitch Creek gneiss, and the 2.55 Ga Mount Owen batholith. The 2.62 Ga Wyoming batholith and Bears Ears granite together represent the most extensive group of granite intrusions that contain abundant SPG: this group of biotite granites extends from the Wind River Range across the Granite, Pedro, and Shirley Mountains, and into the Laramie Mountains. Smaller bodies of SPG include the Rocky Ridge garnet granite gneiss in the northern Laramie Mountains, and the Bear Mountain granite in the Black Hills (Fig. 1). Geochemical data for these six suites is available in Online Material Table OM1.

A plot of aluminum saturation index for samples from these suites (Fig 2a) shows that they are overwhelmingly peraluminous. Most contain both weakly and strongly peraluminous compositions, but the Rocky Ridge gneiss and Bear Mountain granite are entirely composed of SPG. Two suites, the Webb Canyon gneiss and Bitch Creek gneiss, are calcic, whereas the others are calc-alkalic to alkali-calcic (Fig. 2b). Most suites span the magnesian/ferroan boundary, but the Webb Canyon gneiss is distinguished by strongly ferroan compositions (Fig 2c). On the basis of these major element characteristics, the suites define three groups: calcic suites containing SPG, calc-alkalic to alkali-calcic suites composed entire of SPG, and calc-alkalic to alkali-calcic suites composed of both weakly and strongly peraluminous rocks (Table 1). This subdivision forms a basis for discussing the variety of sources and petrogenetic processes that produced Archean SPG.

Table 1. Three types of Neoarchean SPG suites in the Wyoming Province.

SPG-bearing suite	Age (Ga)	Location	Geochemical classification (from Fig. 2)	Proportion of SPG
Calcic suites				
Webb Canyon gneiss	2.68	Teton Range	Calcic, ferroan, metaluminous to peraluminous	35%
Bitch Creek gneiss	2.68	Teton Range	Calcic, magnesian, peraluminous	38%
Calc-alkalic to alkali-calcic suites composed entirely of strongly peraluminous granitic rocks				
Bear Mt gneiss	2.59	Black Hills	Calc-alkalic to alkali-calcic, magnesian, strongly peraluminous	100%
Rocky Ridge garnet granite gneiss	2.64	Laramie Mts	Calc-alkalic to alkali-calcic, ferroan to magnesian, strongly peraluminous	100%
Calc-alkalic to alkali-calcic suites with both weakly and strongly peraluminous granitic rocks				
Mount Owen batholith	2.55	Teton Range	Calc-alkalic to alkali-calcic, ferroan to magnesian, peraluminous	33%
Wyoming batholith & Bears Ears granite	2.62	Granite, Laramie, Wind River Mts	Calc-alkalic to alkali-calcic, ferroan to magnesian, peraluminous	37%

Calcic SPG suites

The two calcic granitoid suites are located in the Teton Range. The calcic Webb Canyon Gneiss and Bitch Creek Gneiss crop out in the northern portion of the small, 50 x 16 km area of Archean outcrop exposed in the Teton Range (Frost et al., 2016).

Webb Canyon Gneiss. The Webb Canyon Gneiss is a weakly layered to massive leucogranitic orthogneiss that is exposed as a series of elongate, sheet-like bodies approximately 2 km wide and up to 10 km in length. It generally shows a strong foliation defined by biotite, particularly intense adjacent to contacts with the Layered Gneiss it intrudes. Webb Canyon Gneiss is generally fine-grained, with crystals typically less than 2 mm in their longest dimension. It consists mainly of quartz and albitic plagioclase, along with 5-20% alkali feldspar. Depending on the proportion of alkali feldspar, samples include both trondhjemite and granodiorite. Hornblende and biotite are present in most samples, although samples from the eastern sheet lack hornblende. Garnet is present in some samples and is subhedral to anhedral. Allanite, zircon, titanite, apatite, and secondary epidote are common accessory minerals. Intergrown biotite and oxide is interpreted to suggest that pyroxene was initially present in some samples (Frost et al., 2016). U-Pb zircon age determinations of seven samples of Webb Canyon Gneiss vary from 2686 ± 5 Ma to 2674 ± 5 Ma (Frost et al., 2016).

Bitch Creek Gneiss. The Bitch Creek Gneiss occurs within the older Layered Gneiss of the Teton Range as sill- or dike-like bodies typically 2-5 m wide and approximately 100 m long, and small plutons up to 100 m across. In general, the Bitch Creek gneiss is lighter in color and displays a weaker foliation than Webb Canyon Gneiss. It is trondhjemitic, containing quartz and plagioclase, and almost no alkali feldspar. Biotite is the primary ferromagnesian mineral; hornblende is absent. Garnet is poikilitic, strongly resorbed, and surrounded by a light-colored halo in which biotite is absent. Zircon and allanite are less abundant than in Webb Canyon Gneiss. U-Pb zircon age determinations of two samples of Bitch Creek Gneiss yielded 2686 ± 3 Ma and 2675 ± 6 Ma, identical within error to the range of ages for the Webb Canyon Gneiss (Frost et al., 2016).

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Calc-alkalic to alkali-calcic suites composed entirely of strongly peraluminous granite

The two suites that are entirely SPG are found in the eastern part of the Wyoming Province, one in the northern Laramie Mountains (Da Prat, 2020) and the other in the Black Hills (Gosselin et al., 1988; 1990).

Rocky Ridge Garnet Granite Gneiss. Muscovite garnet granite gneiss is exposed in the northern Laramie Mountains, where it is one of the most extensive rock units, occupying an ourcrop area in excess of 25 km^2 (Da Prat, 2020). The gneiss is folded with amphibolite, granitic gneiss, and various supracrustal rocks. It is composed of quartz, potassium feldspar, plagioclase, garnet, and muscovite with minor biotite. Garnet is 0.1-4 cm and muscovite is <0.1-2 cm in size. Accessory minerals include zircon, spinel, apatite, oxides, and titanite. Locally the unit is sillimanite-bearing. The unit is strongly foliated. Leucocratic lenses, some garnet-bearing, and biotite selvages in biotite ± muscovite schist and hornblende biotite granite gneiss adjacent to the Rocky Ridge SPG are interpreted to suggest that the garnet granite gneiss was formed by partial melting of these older units. Zircon in this unit is sparse, and typically complexly zoned, metamict and altered, and contains high common Pb and high U contents. U-Pb analysis of five samples revealed inherited zircon of ≥3 Ga in all samples. However, despite careful analysis of the least altered areas, a crystallization age was not obtained (Da Prat, 2020). Rocky Ridge Gneiss is constrained by field relations to be younger than 2.72 Ga hornblende biotite granite gneiss and older than the ~2.64 Ga deformation event that produced the foliation in the Rocky Ridge Gneiss.

Bear Mountain granite. The Bear Mountain granite is it exposed along the western flanks of the Black Hills. It occurs as concordant, sill-like bodies of granite, trondhjemite, and granite pegmatite within a well-foliated biotite-plagioclase schist. The granite is composed of quartz (32-35%), plagioclase (23-32%), microcline (20-31%), and muscovite (2-14%). The trondhjemite is composed of quartz (36-40%), plagioclase (26-29%), muscovite (15-22%), and microcline (trace-4%). Accessory minerals in both rock types include garnet, biotite, and apatite (Gosselin et al., 1988). Zircon crystals are highly metamict and altered but preserve local unaltered areas that were dated by McCombs et al. (2004) at 2596 ± 11 Ma.

Calc-alkalic to alkali-calcic suites containing both weakly and strongly peraluminous granite

Neoarchean granite occupies the majority of outcrop across the central Wyoming Province, from the Wind River Range to the Laramie Mountains. In the Granite, Pedro, Shirley, and Laramie Mountains this 2.62 Ga granite is known as the Wyoming batholith (Bagdonas et al., 2016). In the Wind River Range, several intrusions of granite of the same age and composition are collectively known as the Bears Ears granite (Stuckless, 1989). The southernmost of these plutons is spatially associated with the calc-alkalic 2.63 Ga Louis Lake batholith. Because they are the same age and are indistinguishable compositionally, we group the Wyoming and Bears Ears granites and consider them a single suite of SPG. The other SPG suite in this group, the Mount Owen batholith, is both younger (2.55 Ga) and much smaller (150 km^2)(Frost et al., 2018) than the Wyoming batholith and Bears Ears granite.

Mount Owen batholith. The Mount Owen batholith, which intrudes the central Teton Range, is an undeformed peraluminous leucogranite composed of quartz, alkali feldspar, plagioclase, biotite and muscovite. In some rocks, the dominant mica is biotite and in others it is muscovite. Garnet is present in some samples, and in others sillimanite needles are present in quartz. Zircon is abundant, and allanite and monazite are present in some samples (Frost et al., 2018). The grain-size of the granite is heterogeneous on the outcrop scale, suggesting that water activity was highly variable during emplacement. Pegmatitic and aplitic dikes of Mount Owen affinity are present throughout the range, extending many kilometers away from the main intrusion. Some pegmatitic dikes contain tourmaline. The Mount Owen batholith was emplaced at 2547 ± 3 Ma (Zartman and Reed, 1998).

Wyoming batholith and Bears Ears granite. The 2.62 Ga Wyoming batholith occupies Archean exposures in the Granite, Pedro, Shirley, and Laramie Mountains (Bagdonas et al., 2016). It is composed of two units: biotite granite and leucocratic banded granite. Homogeneous, undeformed biotite granite occupies 90% of outcrops. It is a medium to coarse-grained unit composed of microcline, quartz, plagioclase, and biotite. Accessory minerals include titanite, magnetite, zircon, apatite, and secondary epidote. Trace amounts of muscovite are present in some samples. Leucocratic banded granite makes up approximately 10% of outcrops and is present across the Wyoming batholith. It appears to be more common along batholith margins and near the roof of the batholith. Leucocratic banded granite is more quartz-rich than the biotite granite and contains up to 5% magnetite. Compositional banding is defined by biotite and most likely formed due to magmatic flow. Magnetite can be centimeters in diameter and appears to have formed at the expense of biotite (Bagdonas et al., 2016). The roof of the batholith is most extensively exposed in the northern Laramie Mountains, where it shallowly underlies older schists and granitic gneisses (Da Prat, 2020). There the Wyoming batholith changes from medium-grained and equigranular to coarse-grained and pegmatitic. Pegmatite contains muscovite ± garnet ± tourmaline in addition to alkali feldspar, quartz, plagioclase, and biotite.

Pegmatite dikes and sills intrude the older gneisses above the contact with the Wyoming batholith (Da Prat, 2020).

The type locality of the Bears Ears granite in the southern Wind River Mountains is interpreted to be the youngest component of the calc-alkalic Louis Lake batholith (Frost et al., 1998). It is an undeformed, equigranular to porphyritic biotite granite. In this locality, the contacts with the slightly older granodiorite and quartz diorite rocks are gradational in places, and in other places the Bears Ears granite crosscuts the older units. Two samples were dated at 2.62 Ga by Wall (2004), indistinguishable within error from two dates of the Wyoming batholith by Bagdonas et al. (2016). In our data compilation, we include Bears Ears granite samples from the type locality as well as samples from the New Fork Lakes and Middle Mountain areas of the Wind River Range as part of the Bears Ears granite (Table OM-1). These are plotted together with the Wyoming batholith data on figures 2-6.

Geochemical characteristics of Wyoming Province SPG

Geochemistry of calcic suites

Although the Webb Canyon and Bitch Creek gneisses are both calcic and only subtly distinguishable in the field and in thin section, many aspects of their major and trace element characteristics are quite different (Frost et al., 2016; Table OM1).

Webb Canyon Gneiss is silica-rich, with SiO_2 varying from 70-80%. Alumina contents are relatively low, such that one third of the samples are metaluminous, another third only weakly peraluminous, and the final third are strongly peraluminous (Fig 2a). Most samples are strongly ferroan, apart from six samples from the eastern sheet that lack hornblende (Fig. 2c). (These six samples have higher MgO and lower CaO and Sr than other Webb Canyon gneiss

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samples.) K_2O/Na_2O is variable, reflecting variable modal alkali feldspar content (Fig. 3). Al_2O_3/TiO_2 is low, primarily reflecting the low alumina content of these rocks (Fig. 4).

Compared to the Webb Canyon Gneiss, the Bitch Creek Gneiss has lower SiO_2 (64-75%) and higher alumina than the Webb Canyon Gneiss. As a result, only the most mafic sample is metaluminous (Fig. 2a). Bitch Creek Gneiss samples have low K_2O/Na_2O ratios, reflecting the near-absence of alkali feldspar (Fig. 3). Most samples are magnesian (Fig. 2c). CaO/Na_2O is high, reflecting the plagioclase-rich nature of these rocks, and Al_2O_3/TiO_2 is low due to the relatively high TiO_2 contents of this unit (Fig. 4).

Trace element characteristics of Webb Canyon Gneiss also contrast with those for Bitch Creek Gneiss. Zirconium is higher (240-830 ppm) in the Webb Canyon Gneiss and lower (70-400 ppm) in the Bitch Creek Gneiss (Fig. 5). Neither gneiss contains significant inherited zircon (Frost et al., 2016), thus zircon saturation temperatures of >900°C and 750-900°C respectively suggest that Webb Canyon Gneiss magmas were hotter than Bitch Creek Gneiss magmas. Sr contents of the Webb Canyon Gneiss are relatively low, from 20 to 200 ppm, whereas Bitch Creek gneisses have higher Sr contents averaging 300 ppm (Fig. 6). Similarly low Rb contents in both sets of gneisses yield higher Rb/Sr in the Webb Canyon gneisses (Fig. 6). Ba varies from 100 to nearly 3500 ppm in the Webb Canyon gneiss, whereas Ba is less than 100 ppm in Bitch Creek Gneiss. As a result, Webb Canyon Gneiss exhibits a large range in Sr/Ba compared to the Bitch Creek Gneiss (Fig. 6b).

The Webb Canyon and Bitch Creek gneisses also have distinct rare earth characteristics (Fig. 7a). The Webb Canyon Gneiss is REE-enriched. Patterns are relatively flat and most samples have a deep negative Eu anomaly. Five Webb Canyon samples have slightly lower REE contents and lack Eu anomalies. These samples contain abundant plagioclase and are higher in

CaO and lower in K_2O than other samples. REE abundances of Bitch Creek gneisses are lower, Eu anomalies are modest and include both positive and negative anomalies, and patterns are LREE-enriched and HREE-depleted (Fig. 7a). Both Webb Canyon and Bitch Creek gneisses have positive initial ε_{Nd} isotopic compositions that are consistent with a common, relatively juvenile source (Frost et al., 2016).

Petrogenesis of calcic SPG. Frost et al. (2016) noted that the different roles of plagioclase and hornblende can explain the different geochemical characteristics of the two different calcic SPG suites in the Teton Range. High Sr and alumina in the Bitch Creek Gneiss likely reflects that melting of plagioclase played a role in the formation of that magma. On the other hand, lower Sr and alumina in the Webb Canyon Gneiss samples, along with negative Eu anomalies, indicate plagioclase fractionation or retention in the source. High Y and REE contents may indicate the melting of hornblende or garnet in the production of Webb Canyon magmas.

Experimental studies help to identify the sources and petrogenetic processes that may be responsible for the two types of calcic SPG-bearing suites. Beard and Lofgren (1991) conducted partial melting experiments on greenstone and amphibolite from the Jurassic Smartville complex of California at 850-1000°C and pressures up to 6.9 kb. Although the partial melts obtained in water-excess and dehydration melting experiments were both strongly calcic, in other respects they were quite different (Fig. 8a-c). In the water-excess experiments, plagioclase broke down, yielding an amphibole-rich restite and a strongly peraluminous melt. In the dehydration melting experiments, quartz and amphibole broke down to produce pyroxenes in the restite and mildly peraluminous to metaluminous granodioritic and trondhjemite melts. These experiments suggest that water-excess melting by the reaction hb + pl + qz + vapor = melt, in which plagioclase breaks down leaving an amphibole-rich restite, should produce magmas higher in alumina and

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lower in FeO, along with higher Sr and depleted HREEs, all characteristics observed in Bitch Creek gneisses. By contrast, dehydration melting involving breakdown of amphibole and quartz by the reaction hb + qz = pl + opx + cpx + melt can account for the low alumina, high FeO^t, high silica content and trace element characteristics of the Webb Canyon gneiss. The water-excess melting that produces the Bitch Creek gneiss composition takes place at lower temperature than the dehydration reaction that generates the Webb Canyon gneiss composition, as is also suggested by the lower zircon-saturation temperatures of the Bitch Creek Gneiss (Figs. 5, 9).

Tectonic implications. The Neoarchean rocks of the northern Teton Range have been interpreted to record lateral, collisional orogeny. Mafic and metapelitic rocks were tectonically buried to depths of >12 kb and reached temperatures of >900°C at 2695 Ma. This crust was exhumed and juxtaposed with juvenile metasediments and mafic rocks at 2685 Ma (Swapp et al., 2018). Shortly thereafter and for as long as 10 million years following, Webb Canyon and Bitch Creek leucogranites that formed by dehydration melting and water-excess melting were emplaced (Frost et al., 2016). This history is analogous to Cenozoic continental collisions such as the Alps or Himalayas (Swapp et al., 2018).

Calcic peraluminous magmas in collisional environments may form by either water-excess melting or dehydration melting of hb-pl-bearing rocks. Water-excess melting may occur when relatively cool and hydrous rocks are thrust under hotter rocks. The water released from the lower plate invades the hotter upper plate, inducing melting. Dehydration melts are likely to occur when dramatically overthickened crust undergoes gravitational collapse and tectonic extension, and partial melting takes place in response to decompression (Frost et al., 2016).

Geochemistry of suites that are entirely composed of SPG

The Rocky Ridge and Bear Mountain suites include the most strongly peraluminous granitic rocks of the Wyoming Province, with all samples having ASI > 1.1. Samples from both suites are characterized by very low Zr and TiO_2 contents.

Rocky Ridge garnet granite gneiss. Although all Rocky Ridge garnet granite gneiss samples are strongly peraluminous, the suite includes samples with a range of major and trace element characteristics. Silica ranges from 72 to 78% SiO_2 with one outlier at 68% SiO_2, and compositions vary from ferroan to magnesian, and calc-alkalic to alkali-calcic (Fig. 2). K_2O/Na_2O varies from 0.3 to 2.5 (Fig. 3). CaO/Na_2O is variable, and Al_2O_3/TiO_2 are variable but generally high due to low TiO_2 contents (Fig. 4).

Zr contents of Rocky Ridge garnet granite gneiss are very low (12-110 ppm; Fig. 5). The sparse zircon in this unit is overwhelmingly dominated by inherited grains (Da Prat, 2020) and therefore calculated zircon saturation temperatures based on observed Zr contents overestimate magmatic temperatures. Rb/Ba and Rb/Sr ratios are variable but include the highest ratios of all Wyoming Neoarchean SPG. Sr, Ba, and Y contents are low. REE patterns tend to be LREE-enriched with variable, positive to negative Eu anomalies (Fig. 7). HREE contents vary and are highest in the samples with the most garnet.

Bear Mountain granite. The Bear Mountain granite, like the Rocky Ridge garnet granite gneiss, is entirely composed of strongly peraluminous rocks (Fig. 2a). The suite includes both trondhjemites, which are magnesian, and granites, which are magnesian to ferroan (Fig. 2c). All samples have similar silica and alumina contents and low CaO. The trondhjemite samples are calc-alkalic to calcic and have low K_2O, whereas and the granite samples are alkali-calcic to alkalic and have higher K_2O (Fig 2bc, 3). These geochemical differences reflect variations in the modal abundance of alkali feldspar and muscovite in these rock types. CaO/Na_2O is low and Al_2O_3/TiO_2 is high due to low TiO_2 (Fig. 4).

Zr contents are very low (5-80 ppm) and yield zircon saturation temperatures of 550-800°C (Fig. 5). Rb/Ba, Rb/Sr, and Sr/Ba are high (Fig. 6). Y and REE abundances are low. REE patterns for trondhjemite are lower and flatter than patterns for granite. Eu anomalies are mostly pronounced and negative but two are slightly positive (Fig. 7). Sr and Eu contents are strongly correlated (Gosselin et al., 1990).

Interpretation of suites that are entirely SPG. Field relations between SPG and micaceous schists led Da Prat (2020) and Gosselin et al. (1990) to suggest that the Rocky Ridge and Bear Mountain SPG formed by partial melting of metasedimentary rocks. The uniformly siliceous and strongly peraluminous nature of these gneisses is compatible with this hypothesis. Although it is possible to produce peraluminous residual melts by fractionation of aluminum-poor phases such as hornblende or pyroxene from metaluminous magma (Cawthorn and Brown, 1976; Zen, 1986), and marginally peraluminous melts can be driven to more peraluminous compositions by fractionation of feldspars (Clarke, 2019), these processes are more likely to result in rocks with a range of silica contents and weakly peraluminous ASI rather than strongly peraluminous leucogranites.

Geochemical characteristics of these rocks are best explained by anatexis of a metasedimentary source. Experimental data show that melting of muscovite-bearing metapelitic schist can produce SPG that vary from magnesian to ferroan, and that are calc-alkalic to alkali-calcic (Fig. 8d-f), similar to the characteristics observed in Bear Mountain and Rocky Ridge granites. Compared to other Neoarchean SPG in the Wyoming Province, the Bear Mountain and Rocky Ridge granites are distinguished by very low Zr contents and variable but low zircon saturation temperatures (550-800°C)(Fig. 5). As noted above, these units contain sparse, complexly zoned and mottled zircon. In the Rocky Ridge gneiss, the U-Pb systematics of these zircon indicate that they are older, inherited grains. Including Zr held in these grains in the zircon saturation temperature calculation yields temperatures that are too high. Da Prat (2020) concluded that the temperature determination of 670-690°C obtained using metamorphic assemblage diagrams is a better estimate of magma temperature.

Low magma temperatures are consistent with the low TiO_2 and Ba contents and high Al_2O_3/TiO_2 of the Bear Mountain and Rocky Ridge granites (Table OM1, Fig. 5). Ti and Ba are compatible in biotite, and their low abundances in the SPG gneisses suggest that biotite was not involved in the melting reactions. Biotite dehydration melting takes place at temperatures above 720°C (Le Breton and Thompson, 1988), higher than the temperature calculated for Rocky Ridge gneiss. We therefore suggest that the melt-forming reaction for these SPG rocks involved melting of muscovite in a metasedimentary source.

The Bear Mountain and Rocky Ridge SPG also tend to have low calcium relative to sodium, with most samples $CaO/Na_2O < 0.2$. Low ratios can indicate a clay-rich source: partial melting experiments have shown that during vapor-absent melting of plagioclase-poor pelitic rock, sodium entered the melt but calcium was retained in residual garnet, yielding melts with CaO/Na_2O of 0.1 - 0.3 (Fig. 10a; Castro et al., 1999; Patino Douce and Harris, 1998; Pickering and Johnston, 1998). The slightly higher CaO/Na_2O of some Bear Mountain and Rocky Ridge SPG might be due to more plagioclase-rich source rocks: experiments with such starting compositions gave melts with higher CaO/Na_2O (Fig 10b). Or, the higher ratios may be attributable to vapor-present melting, which has been shown to lead to more extensive melting of plagioclase and higher CaO/Na_2O in the melt (Holtz and Johannes, 1991).

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The ratios of Rb, Sr, and Ba, which are held mainly in micas and feldspars, differ in Bear Mountain and Rocky Ridge SPG. Rocky Ridge samples have low Sr/Ba (especially for samples with low CaO/Na_2O) and high Rb/Ba and Rb/Sr. By contrast, Bear Mountain samples are distinguished by high Sr/Ba, especially for trondhjemites, high Rb/Ba, and somewhat lower average Rb/Sr. Low Sr/Ba in Rocky Ridge samples may indicate retention of plagioclase in the restite, as is expected for vapor-absent muscovite dehydration melting because little melt is produced (Harris and Inger, 1992). High Sr/Ba in Bear Mountain, particularly for the trondhjemites, likely indicates greater consumption of plagioclase during vapor-present melting, a process that would also produce their observed high Na_2O/K_2O (Fig. 3) (Castro et al., 1999; Patiño Douce and Harris, 1998). Interpretation of the other ratios is less definitive. High Rb/Ba and Rb/Sr, when coupled with low CaO/Na_2O, may indicate a clay-rich source (Harris and Inger, 1992). However, ratios of Rb/Ba and Rb/Sr in the melt also depend upon the amount of residual plagioclase and K-feldspar. Knowledge of the abundances of these elements in the magma sources as well as the residual mineralogy of the partial melting reactions would be needed to distinguish these alternatives (Nabelek, 2020).

Rocky Ridge and Bear Mountain granites have the lowest REE contents of any of the Wyoming Neoarchean SPG (Fig. 7b). This may reflect the retention of REE-bearing accessory minerals like zircon and monazite in the source during low-temperature anatexis, as was suggested for the Proterozoic Harney Peak SPG in the Black Hills, South Dakota (Nabelek and Glascock, 1995).

Tectonic implications. Strongly peraluminous granite intrusions formed by low-temperature anatectic melting of metasedimentary rocks are commonly found within collisional orogens (Sylvester, 1998). Sedimentary rocks are overridden during continent-continent collision. The collision results in crustal thickening accompanied by heating of the sedimentary sequence, followed by gravitational collapse. Partial melting may occur when deeply buried metasedimentary rocks intersect muscovite dehydration melting reactions during decompression, producing SPG melts. Other mechanisms such as flux melting also may result in SPG anatexis and magma production in collisional orogens (Nabelek, 2020), and may have contributed to the formation of some Bear Mountain SPG, especially the trondhjemites.

Calc-alkalic to alkali-calcic suites with both weakly and strongly peraluminous granite

The Mount Owen batholith is a peraluminous leucogranite with a limited range of silica contents (SiO_2 = 73.7% to 75.7%, plus one sample with 71.6%). One-third of the samples are strongly peraluminous; these tend to be alkali-calcic whereas weakly peraluminous samples are calc-alkalic (Fig. 2ab). Samples vary from ferroan to magnesian, with strongly peraluminous samples tending to be magnesian (Fig. 2c). The strongly peraluminous samples have $K_2O>Na_2O$ (Fig. 3). They have lower CaO/Na_2O, Al_2O_3/TiO_2, and Zr abundances than the weakly peraluminous samples (Figs. 4, 5). Mount Owen leucogranite has high Rb/Ba and Rb/Sr and low Sr/Ba, similar to the Rocky Ridge SPG (Fig. 6).

Wyoming batholith and Bears Ears granite group of samples exhibit a larger range of silica (SiO_2 = 70.2% to 77.1%) than do Mount Owen batholith samples. Like the Mount Owen batholith, the strongly peraluminous samples of the Wyoming batholith and Bears Ears granite are more alkali-calcic on average than the weakly peraluminous samples (Fig. 2ab). Both strongly and weakly peraluminous samples span the ferroan-magnesian boundary (Fig. 2c) and both have $K_2O > Na_2O$ (Fig. 3). Al_2O_3/TiO_2 is relatively low except for pegmatitic samples from the roof zone of the Wyoming batholith in the northern Laramie Mountains (Fig. 4). Both

CaO/Na_2O and Zr are quite variable (Figs. 4, 5). Zr contents and zircon saturation temperatures are higher than for the Mount Owen batholith (Fig. 5). Rb/Ba, Rb/Sr and Sr/Ba are intermediate between the calcic and entirely SPG suites (Fig. 6ab).

Mount Owen granites are LREE-enriched with negative Eu anomalies, but less strongly LREE-enriched than the Bears Ears and Wyoming batholith (Fig. 7cd). With the exception of samples from the pegmatitic roof zone to the Wyoming batholith, which share the geochemical characteristics of the the entirely SPG suites, Wyoming batholith granites exhibit LREE-enriched patterns with deep negative Eu anomalies. The Bears Ears granites have similar LREE-enriched patterns, although several samples with the lowest REE have positive Eu anomalies suggesting feldspar accumulation (Fig. 7d). LREE abundances of the Wyoming batholith and Bears Ears granite are higher than for any other suite except for the calcic Webb Canyon gneiss. Four pegmatite samples from the northern Laramie Mountains have flatter patterns and lower REE contents than the biotite granite that makes up the majority of the batholith (Fig. 7d).

Interpretation of suites containing weakly and strongly peraluminous granitic rocks.

Although the Mount Owen and the Wyoming batholith suites share some similarities, including both weakly and strongly peraluminous granitic rocks and overlapping MALI, Fe-indices, and K_2O/Na_2O (Figs. 2bc, 3), other features suggest they originated from different sources and petrogenetic processes. The smaller 2.55 Ga Mount Owen batholith intrudes older Neoarchean Layered Gneiss that is composed of quartzofeldspathic gneiss, metagraywacke, and amphibolite (Frost et al., 2018). Calculated zircon saturation temperatures for the Mount Owen batholith of 690-870°C are higher than those estimated for the Rocky Ridge SPG gneiss (670-690°C; Da Prat, 2020). Its lower Al_2O_3/TiO_2 compared to the solely SPG suites also suggests higher magma temperatures and the involvement of biotite in melting reactions. Higher CaO/Na_2O compared to the entirely SPG suites is consistent with a more plagioclase-rich source (Fig. 10), and the initial Nd isotopic compositions of the Mount Owen batholith are within the range of the initial Nd isotopic compositions of the Layered Gneiss (Frost et al., 2006a; 2016). Taken together, these characteristics suggest breakdown of biotite during partial melting of graywacke and/or quartzofeldspathic gneiss by a reaction such as bt + q + pl = opx + orthoclase component of plagioclase + gar + melt (Vielzeuf and Montel, 1994). In other words, the Mount Owen batholith, and Rocky Ridge and Bear Mountain SPG all formed by crustal melting, but the Mount Owen source rock was more biotite- and plagioclase-rich.

The Wyoming batholith and Bears Ears granite are by far the most voluminous of the Neoarchean SPG suites in the Wyoming Province. Field relations suggest that Bears Ears granite is closely related to the 2.63 Ga Louis Lake batholith, a continental arc batholith that occupies the southern half of the Wind River Range (Frost et al., 1998). Geochemical and isotopic data are consistent with formation of the Bears Ears granite by differentiation from Louis Lake granodiorites (Bagdonas et al., 2016). The Bears Ears granite is geochemically indistinguishable from the Wyoming batholith, which led Bagdonas et al. (2016) to suggest that similar magma sources supplied all the 2.62 Ga granites. This hypothesis implies that the subduction-related input of mantle-derived heat and magma was widespread across the southern Wyoming Province.

Initial Nd isotopic compositions show that although Louis Lake and Bears Ears samples have overlapping initial ε_{Nd}, many Wyoming batholith samples have more negative initial ε_{Nd} indicating that they have either assimilated greater proportions of crust or were contaminated by older, less radiogenic Archean crust (Fig. 11). The initial ε_{Nd} of the strongly peraluminous samples (-3.0) are on average more negative than the weakly peraluminous samples (-1.6), suggesting that assimilation of aluminous crustal melts enhanced the peraluminous nature of the granite magmas. There is a general trend of increasing ASI and decreasing initial ε_{Nd} from west to east (Fig. 12). This trend suggests that the crustal assimilant involved in producing the magmas is more aluminous in the eastern Wyoming Province. The fact that the Rocky Ridge and Bear Mountain SPG are found in this part of the province supports such a hypothesis.

The pegmatitic dikes and sills that form the roof of the Wyoming batholith in the northern Laramie Mountains are both mineralogically and chemically distinct from the main intrusion. They exhibit variable grain sizes and are commonly muscovite-, garnet-, and locally tourmaline-bearing. The Al_2O_3/TiO_2 ratios and trace element compositions of these pegmatitic rocks are similar to Rocky Ridge SPG gneiss, suggesting that they formed by partial melting of aluminous crust in response to heating by Wyoming batholith magma (Figs. 5, 6).

Tectonic implications. Although both the Mount Owen and the Wyoming batholith calc-alkalic to alkali-calcic leucogranite suites contain crustal components, the processes by which they formed are likely to have been different. The Mount Owen batholith most likely formed by crustal melting of a biotite- and plagioclase-bearing metasedimentary rock and/or quartzofeldspathic orthogneiss. In contrast, the Wyoming batholith and Bears Ears granite formed by fractionation of calc-alkaline continental arc magmas, accompanied by assimilation of felsic crust.

Discussion: Petrogenesis of Neoarchean SPG in the Wyoming Province

The three groups of Neoarchean SPG of the Wyoming Province are compositionally distinct and were produced by different petrologic processes, all of which also occur in the Phanerozoic.

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The calcic SPG are best explained by partial melting of hornblende-plagioclase rocks: the Webb Canyon suite formed by dehydration melting and the Bitch Creek suite by water-excess melting. These processes formed trondhjemites with distinctively different major and trace element compositions. Phanerozoic examples of peraluminous trondhjemites formed by partial melting of mafic rocks include the type locality trondhjemites of Trondheim, Norway (Slagstad, 2003), trondhjemites of the Smartville Complex, California (Beard and Lofgren, 1991), trondhjemite dikes in the Blue Ridge Mountains of North Carolina and Georgia (Wood and Miller, 1984), and tonalites and trondhjemites of the Cornucopia Stock of northeastern Oregon (Johnson et al., 1997). The continent-continent collision responsible for the Webb Canyon and Bitch Creek gneisses, in which underthrusting and crustal thickening was followed by gravitational collapse (Swapp et al., 2018) is analogous to Neogene Himalayan collisional processes. The reason that the Archean intrusions are calcic trondhjemites whereas the modern Himalayan leucogranites are true granites is related to the fundamental difference in the composition of the crust in the Tetons and the Himalayas. The crust that partially melted in the Tetons was composed of greywacke, tonalite, and amphibolite. These rocks, which are less potassic than the pelitic sources of the Himalayan leucogranites, also required higher temperatures to partially melt than were required to partially melt the pelitic rocks in the Himalayas (Frost et al., 2016). However, compositional differences aside, the Webb Canyon and Bitch Creek SPG are evidence that the same general processes of melt formation, migration and solidification have taken place in collisional orogens for at least 2.7 Ga.

The petrogenesis of several of the Wyoming SPG suites appears to involve anatexis of metasedimentary rocks. The Rocky Ridge and Bear Mountain suites bear the hallmarks of leucogranitic rocks formed by partial melting of pelitic rocks by reactions involving muscovite.

As such, they are compositionally analogous to other ancient and modern collisional leucogranites formed from metamorphosed, deformed, and partially-melted pelitic rocks including in the Proterozoic Black Hills orogen, the Paleozoic Appalachian orogen, and the Tertiary Himalayan orogen (Nabelek, 2020). The implication is that by 2.6 Ga in the eastern Wyoming Province, processes of erosion and sedimentary recycling had produced aluminous, fine-grained, clastic sedimentary rocks and that these were buried and heated to produce partial melts. On the western side of the Wyoming Province, the 2.55 Ga Mount Owen batholith appears to have formed from more plagioclase-rich crustal sources such as greywacke, by higher-temperature melting reactions involving biotite, suggesting that in this part of the province muscovite-bearing pelitic sources were minor or absent.

The other SPG-forming mechanism that appears to have operated during the Neoarchean in the Wyoming Province is differentiation of continental arc magmas, accompanied by varying amounts of crustal assimilation. This mechanism, which was responsible for the Wyoming batholith and Bears Ears granite, produced far more true granite and strongly peraluminous granite than is typical of Phanerozoic continental arcs. Bagdonas et al. (2016) suggested that the Wyoming batholith represents the plutonic portion of a large rhyolitic system associated with a continental arc, analogous to modern, shallow silicic batholiths that supply rhyolite calderas in the central Andes. The large proportion of granite observed in the Wyoming continental arc system may have formed in response to greater radioactive heat production and mantle power input to the base of the crust in the late Archean, driving more extensive differentiation and assimilation, and forming larger volumes of silicic magma compared to the modern day. The significance of the continental arc setting for these SPG is that this plate tectonic process must have been in place by the Neoarchean.

A summary of the defining characteristics of the Wyoming Neoarchean SPG and their interpretation (Table 2) indicates that plate tectonic processes of continent-continent collision and formation of magmatic arcs on evolved continental margins were established in the Wyoming Province by 2.68-2.60 Ga.

Table 2. Petrogenetic interpretation and tectonic significance of Wyoming Province SPG

SPG Suite and example	**Geochemical characteristics**	**Petrogenetic interpretation**	**Tectonic significance**
Calcic Webb Canyon Gneiss Bitch Creek gneiss	Calcic, low Al_2O_3/TiO_2 and low Rb/Ba, high REE and Zr contents	Partial melting of hb-pl-bearing sources, by dehydration melting (Webb Canyon) or water-excess melting (Bitch Creek)	Collisional orogeny involving partial melting of relatively mafic sources such as tonalite, amphibolite, and graywacke
Alkalic-calcic to calc-alkalic, entirely SPG Rocky Ridge granite gneiss Bear Mountain granite Dikes and sills along roof zone of Wyoming batholith	ASI = 1.1-1.4 and higher, high Al_2O_3/TiO_2 (due to low TiO_2) and high Rb/Ba, low REE and Zr contents, low CaO/Na_2O	Partial melting of ms-bearing sources. Dehydration and water-excess melting; latter forms trondhjemites	Collisional orogeny involving partial melting of metapelitic sources. (Note these SPG also form by partial melting of aluminous crust in response to magmatic heating, as in the roof zone of the Wyoming batholith.)
Alkalic-calcic to calc-alkalic, weakly and strongly peraluminous Mount Owen batholith Wyoming batholith and Bears Ears granite	Intermediate to high CaO/Na_2O, K_2O/Na_2O, Rb/Ba, Zr and REE; intermediate to low Al_2O_3/TiO_2	Partial melting reactions involving biotite (Mount Owen), or differentiation and crustal assimilation by calc-alkalic magmas	Collisional orogeny involving partial melting of bt-rich sources, such as graywacke (Mount Owen), or subduction-related continental arc magmatism (Wyoming batholith and Bears Ears granite)

Implications for crustal evolution

Various geochemical indicators suggest that the continental crust became more felsic in the Neoarchean (e.g., Chen et al., 2020; Dhuime et al., 2015; Tang et al., 2016). Such a change in composition will be reflected in the sedimentary rock record: erosion of K-rich granitic crust followed by multiple cycles of weathering, transport, and deposition produces shale with a characteristic geochemical composition (Taylor and McLennan, 1985). Subsequent burial and metamorphism of shale produces metapelite, that when partially melted, forms SPG. Therefore, the appearance in the rock record of SPG that formed by partial melting of metapelitic rocks is powerful confirmation of this evolution in the composition of the Earth's crust.

This geochemical shift was not synchronous, either on local or global scales. The results of this study indicate that the crustal sources to the SPG examined in this study vary across the Wyoming Province, from more plagioclase-rich sources with more radiogenic Nd isotopic compositions in the west and more felsic, potassic crust with less radiogenic Nd isotopic compositions in the east (Fig. 12). Given that Archean cratons are commonly composed of subprovinces with distinct geologic histories, it is not surprising that the age and composition of the crust should vary spatially across a given province.

Worldwide, SPG interpreted to have formed by partial melting of metasedimentary rocks appear in the rock record at different times on different cratons. In their review, Bucholz and Spencer (2019) identified two Mesoarchean suites that include some SPG: the ~3.07 Ga Sinceni intrusion and other latest Mesoarchean two-mica granites that intrude the Pongola Supergroup in the Kaapvaal craton, and the 3067 Ma Annandagstoppane granite that is exposed in a very small area of the Grunehogna craton of East Antarctica. However, most SPG formed later. They appear on at least four different Archean cratons in the Neoarchean: in the Superior province (2.68-2.66

Ga), in Wyoming (>2.64-2.60 Ga), Slave (2.61-2.59 Ga), and Yilgarn (2.63-2.63 Ga) (Bucholz and Spencer, 2019; this study). In these Archean provinces, the intrusion of SPG are among the final events prior to cratonization, that is, the time after which they experience no penetrative deformation and calc-alkalic magmatism and deformation. Other Archean provinces cratonized later and the oldest SPG in those cratons also formed later. For example, in the North China Craton, SPG appear at between 1.90-1.93 Ga, immediately followed by final Paleoproterozoic assembly of the Western Block of the craton (Bucholz and Spencer, 2019; Zhao et al., 2005).

The global "bloom" of Neoarchean SPG follows the emergence of continental arcs above subduction zones at the end of the Mesoarchean (Brown and Johnson, 2018), and coincides with the assembly of the first supercontinents (Campbell and Allen, 2008). Both subduction beneath a continental plate margin and amalgamation of crustal blocks by collisional orogeny provide tectonic environments that transport sedimentary rocks to depths where partial melting occurs. SPG record both of these environments in the Wyoming Province. Subduction beneath a continental arc at 2.62 Ga is recorded by the Wyoming batholith and Bears Ears granite. The remaining SPG record collisional orogenies occurring around the edges of the Wyoming Province. The collisions at 2.68 Ga and 2.55 Ga in the Tetons are incompletely understood because subsequent Proterozoic orogenies along the western and northern margins of the Wyoming Province have removed much of the evidence. In southern Wyoming the ~2.64 Ga Rocky Ridge SPG was intruded then deformed at the time when accreted terrains docked along the southern margin of the province (Fig. 1)(Frost et al., 2006b), and the 2.60 Ga Bear Mountain SPG formed at the same time as monazite and hydrothermal zircon growth (Bagdonas et al., 2016; Vincent, 2017). These events may be related to the collision of Wyoming and Superior provinces to create Neoarchean-Paleoproterozoic supercontinent Superia, a supercontinent that rifted apart at ~2480 Ma and was rejoined along the Trans-Hudson orogen at ~1760 Ma (Dahl et al., 2006; Davey et al., 2020; Ernst and Bleeker, 2010; Redden et al., 1990; Van Boening and Nabelek, 2008).

In summary, the appearance of SPG in the Neoarchean rock record coincides with the time when the continental crust became strong, thick, and evolved enough to support large, elevated continental landmasses (Kump and Barley, 2007). Weathering and erosion of this subaerial crust enabled the production and deposition of fine-grained, aluminous sediment sources that are parental to many SPG. The establishment of strong crustal blocks also enabled modern plate tectonic processes of subduction and continental collision, which take sedimentary rocks from the Earth's surface to depth where they are metamorphosed and partially melted to form SPG. Amalgamation of cratons by collisional orogenesis formed the Earth's first supercontinents, an evolutionary development recorded by formation and emplacement of voluminous SPG.

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Figure captions

Fig. 1. Map of the Wyoming Province, showing locations of Neoarchean SPG. Archean rocks of the Wyoming Province are exposed in Wyoming, Montana, and in the Black Hills of South Dakota. The boundary of the Wyoming Province with Proterozoic provinces to the south is exposed only in southeastern Wyoming along the Cheyenne belt (solid line); it is dashed where inferred. The biotite granite of the Bears Ears and Wyoming batholith are grouped together as a single suite of SPG; the others are the Bear Mountain granite, Rocky Ridge garnet granite gneiss, Webb Canyon gneiss, Bitch Creek gneiss, and the Mt. Owen batholith.

Fig 2. (a) Aluminum saturation index (ASI), (b) Modified alkali-lime index (MALI), and (c) Fe-index for Wyoming Neoarchean SPG suites. Filled symbols are samples with ASI>1.1, open symbols are samples with ASI < 1.1. Circled Wyoming batholith and Bears Ears samples are those from the roof zone of the Wyoming batholith in the northern Laramie Mts. Bear Mt samples marked by yellow squares are granites, yellow squares with plus symbol are trondhjemites. Boundaries for MALI are from Frost et al. (2001) and for Fe-index are from Frost and Frost (2008). Data are compiled on Table OM1 from Bagdonas et al. (2016), Cornia (2003), Da Prat (2020), Frost et al. (2016), Frost et al. (2018), Gosselin et al. (1990), Stuckless (1989), Wall (2004), and Wilks (1991).

Fig 3. Wt.% K_2O content plotted as a function of wt.% Na_2O content for Wyoming SPG. Dashed line indicates $K_2O = Na_2O$. Symbols and data sources as in Fig 2.

Fig. 4. CaO/Na_2O v. Al_2O_3/TiO_2 for Wyoming SPG. Symbols and data sources as in Fig 2.

Fig 5. Zr content (in ppm) vs wt.% SiO_2 for Wyoming SPG, contoured for approximate zircon saturation temperatures (Boehnke et al., 2013). Symbols and data sources as in Fig. 2.

Fig 6. (a) Rb/Ba v. Rb/Sr and (b) and Sr/Ba v. Rb/Sr for Wyoming SPG. Symbols and data sources as in Fig. 2.

Fig 7. REE patterns for Wyoming SPG suites. (a) Calcic suites, represented by Webb Canyon and Bitch Creek gneisses, (b) suites entirely composed of SPG, represented by the Rocky Ridge and Bear Mountain granites, and suites composed of both weakly and strongly peraluminous granitic rocks, including the Mount Owen batholith (c), and the Wyoming batholith and Bears Ears granite (d). Data sources as in Fig. 2.

Fig 8. Experimental results for partial melting of Hb-Pl-bearing rocks (a-c), Ms-Bt-rocks (d-f), and Bt-bearing rocks (g-i). Closed symbols = dehydration melting; open symbols = water excess melting. Data for Hb-Pl-bearing rocks are from Beard and Lofgren (1991). Starting compositions for melt compositions from Ms-Bt-bearing rocks include two-mica gneiss (Castro et al., 1999), muscovite schist (Patiño Douce and Harris, 1998), and metapelite (Pickering and Johnston, 1998). Starting compositions for melt compositions from Bt-bearing rocks include biotite gneiss (Holtz and Johannes, 1991; Patiño Douce and Beard, 1995), greywacke (Conrad et al., 1998), synthetic Fe-rich biotite gneiss (Patiño Douce and Beard, 1996), and cordierite-bearing paragneiss (Koester et al., 2002). Data were obtained from the compilation by Gao et al. (2016).

Fig 9. Experimental and thermodynamically predicted positions of water-excess melting and dehydration melting of Hb-Pl rocks, showing that the water-excess melting reactions that formed the Bitch Creek gneiss took place at lower temperature than the dehydration melting reactions that produced the Webb Canyon gneiss. Modified from Frost et al. (2016).

Fig 10. CaO/Na_2O and Al_2O_3/TiO_2 ratios of experimental partial melts produced by dehydration and water-excess melting of (a) 2-mica gneiss, schist and metapelitic rocks and (b) graywacke and biotite paragneiss, showing the higher CaO/Na_2O characteristic of the latter. Closed symbols = dehydration melting; open symbols = water excess melting. Sources as for Fig. 8d-f.

Fig 11. Initial ε_{Nd} of Wyoming batholith and Bears Ears granite. Open diamonds represent weakly peraluminous samples and closed diamonds represent strongly peraluminous samples. All samples were intruded at 2.62 Ga; Wyoming batholith and Bears Ears samples are offset slightly for clarity. Also shown are potential magma sources, including the 2.63 Ga Louis Lake Batholith (LLB) in the Wind River Range with which the Bears Ears granite is spatially related, older Archean crust of the Granite and Laramie Mountains, evolved metasedimentary rocks of the Granite Mountains, and juvenile sediments of the southern accreted terranes in the Wind River Range and Granite Mountains. Data from Table OM1, Frost et al. (1998; 2006b; 2017), Fruchey (2002), Meredith (2005), and Wall (2004).

Fig 12. Initial ε_{Nd} of Wyoming batholith and Bears Ears granite as a function of longitude, showing more strongly peraluminous and negative ε_{Nd} compositions in the Shirley, Pedro, and

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Laramie Mountains compared to samples from farther west in the Granite Mountains and Wind River Range. Data from Table OM1.

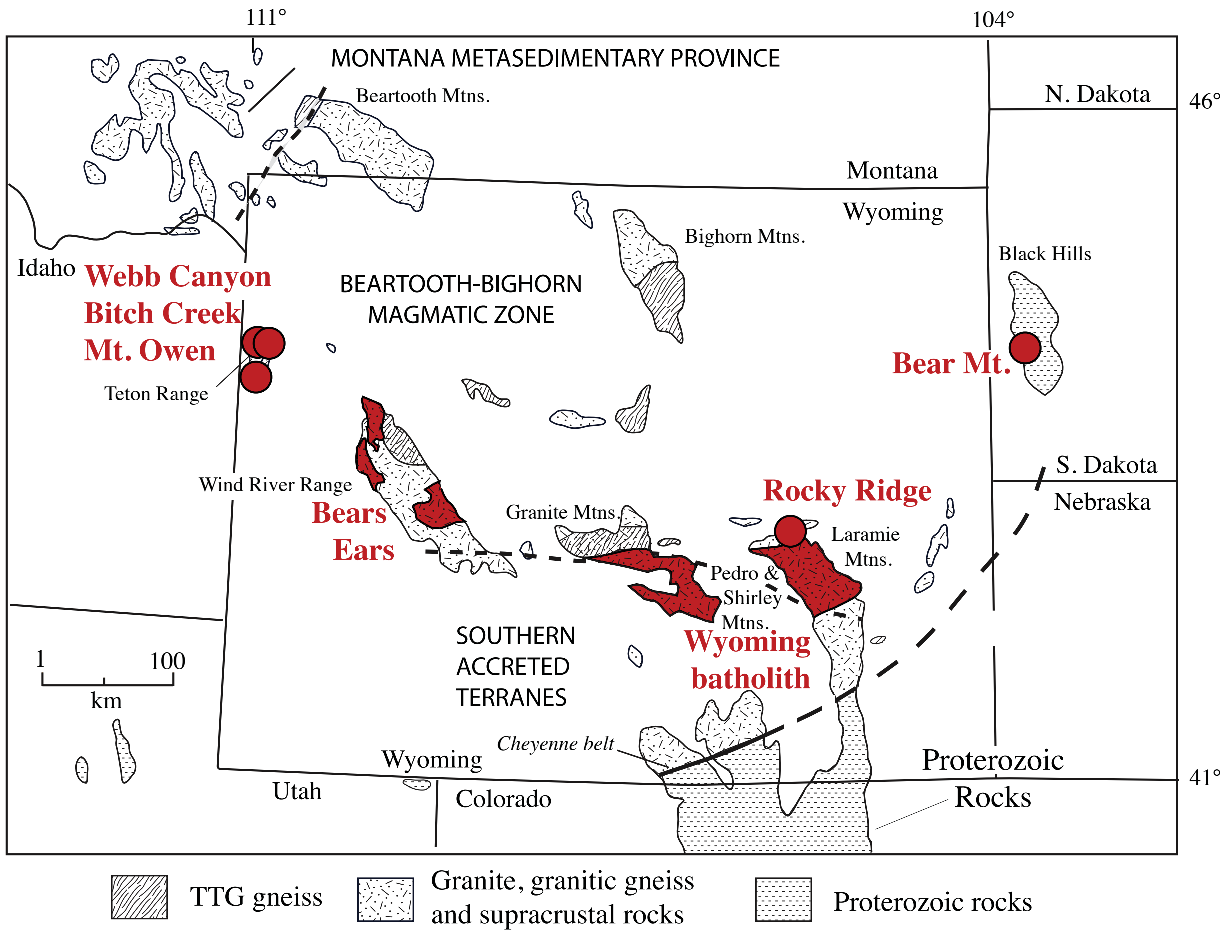
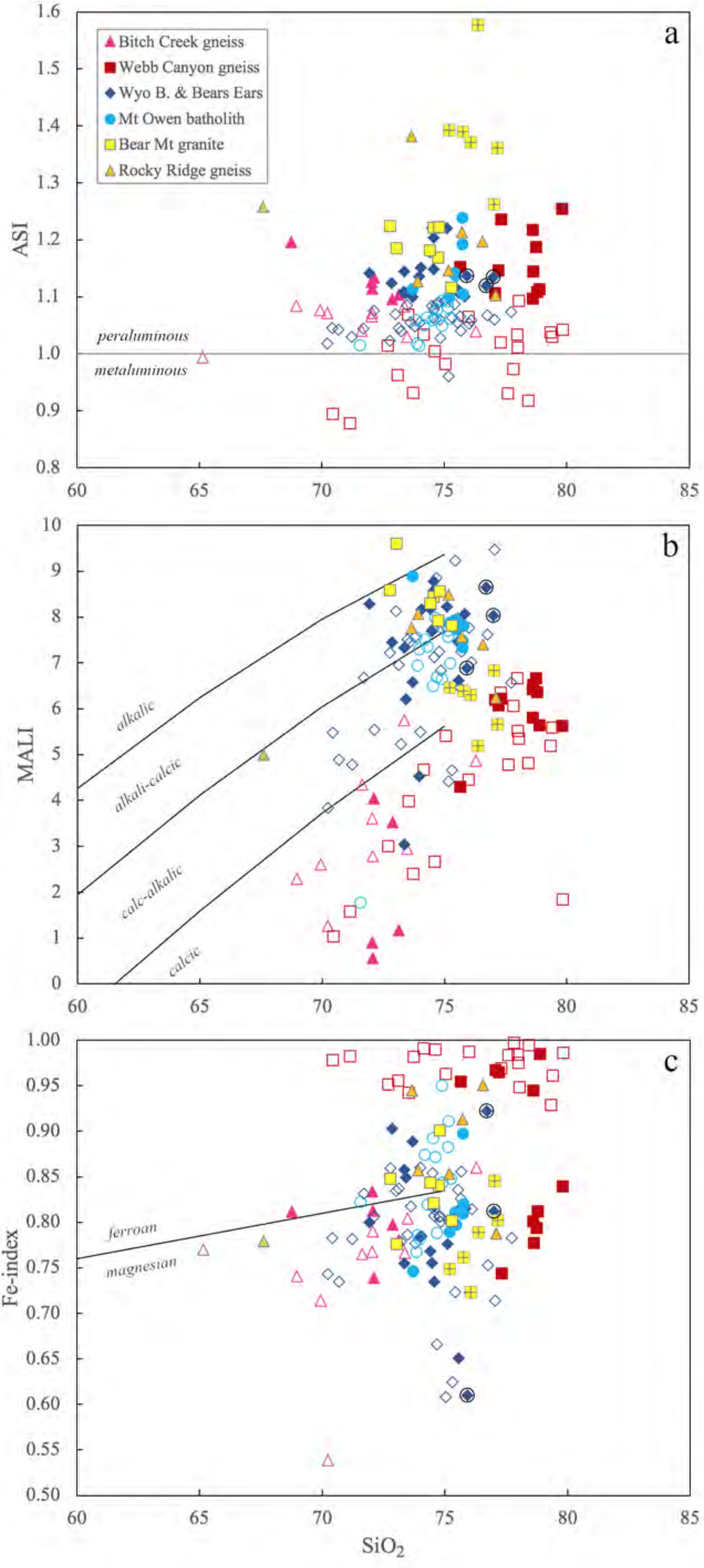

111°
104°
46°
41°
MONTANA METASEDIMENTARY PROVINCE
Beartooth Mtns.
N. Dakota
Montana
Wyoming
Bighorn Mtns.
Black Hills
Idaho
Webb Canyon
Bitch Creek
Mt. Owen
BEARTOOTH-BIGHORN
MAGMATIC ZONE
Teton Range
Bear Mt.
S. Dakota
Nebraska
Rocky Ridge
Wind River Range
Bears
Ears
Granite Mtns.
Laramie
Mtns.
Pedro &
Shirley
Mtns.
Wyoming
batholith
SOUTHERN
ACCRETED
TERRANES
1
100
km
Cheyenne belt
Wyoming
Utah
Colorado
Proterozoic
Rocks
TTG gneiss
Granite, granitic gneiss
and supracrustal rocks
Proterozoic rocks

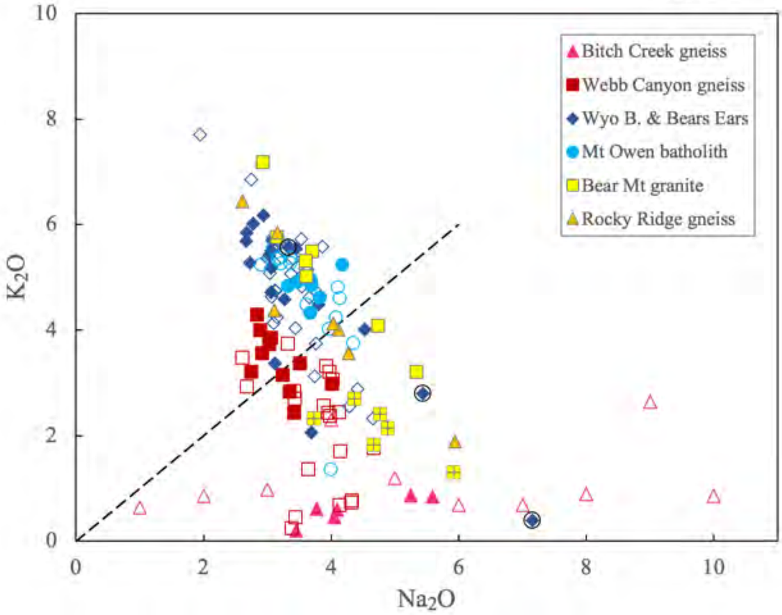
Fig. 1

Fig 2



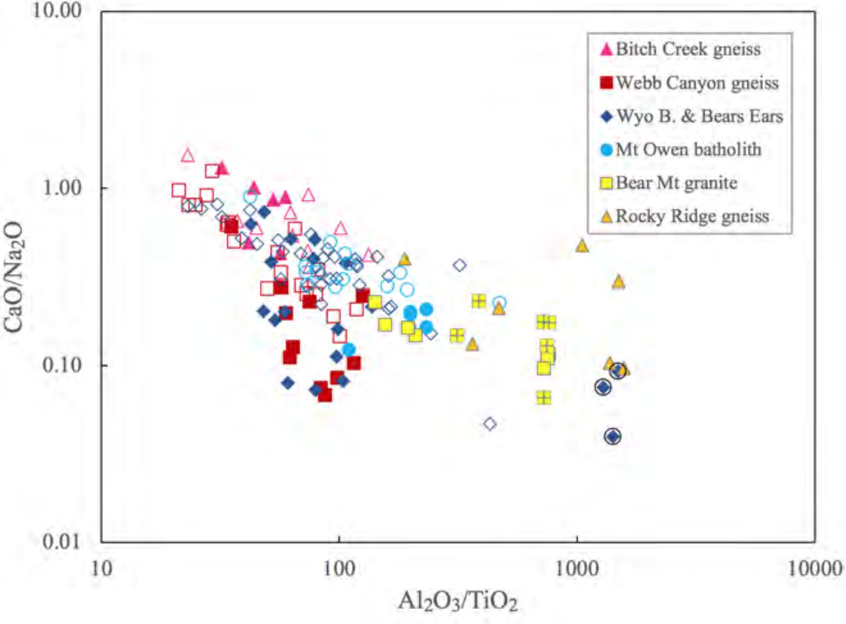
a
Bitch Creek gneiss
Webb Canyon gneiss
Wyo B. & Bears Ears
Mt Owen batholith
Bear Mt granite
Rocky Ridge gneiss
peraluminous
metaluminous
ASI
b
alkalic
alkali-calcic
calc-alkalic
calcic
MALI
c
ferroan
magnesian
Fe-index
SiO2

Figure 3



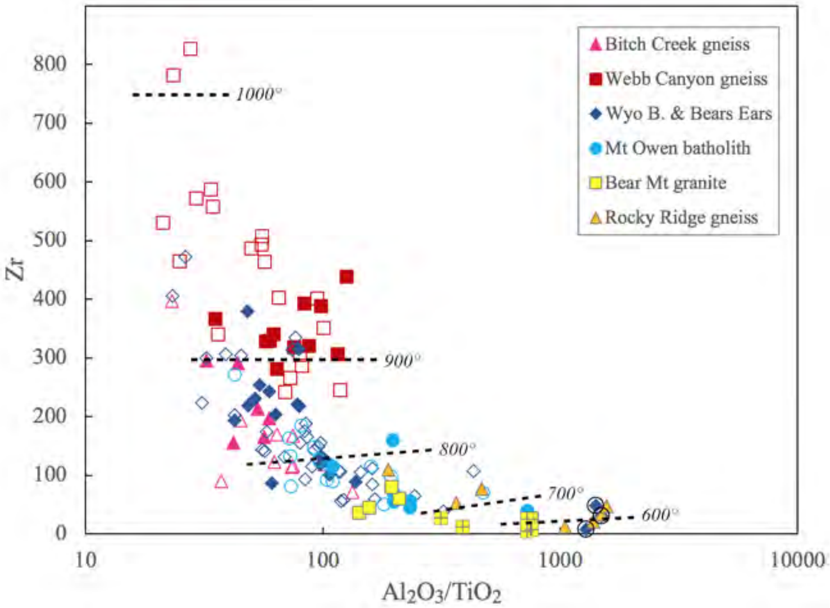
Bitch Creek gneiss
Webb Canyon gneiss
Wyo B. & Bears Ears
Mt Owen batholith
Bear Mt granite
Rocky Ridge gneiss
K_2O
Na_2O
0
2
4
6
8
10

Fig 4



10.00
1.00
0.10
0.01
10
100
1000
10000
CaO/Na2O
Al2O3/TiO2
Bitch Creek gneiss
Webb Canyon gneiss
Wyo B. & Bears Ears
Mt Owen batholith
Bear Mt granite
Rocky Ridge gneiss

Fig 5



Bitch Creek gneiss
Webb Canyon gneiss
Wyo B. & Bears Ears
Mt Owen batholith
Bear Mt granite
Rocky Ridge gneiss
1000°
900°
800°
700°
600°
Zr
0
100
200
300
400
500
600
700
800
10
100
1000
10000
Al2O3/TiO2

Fig 6

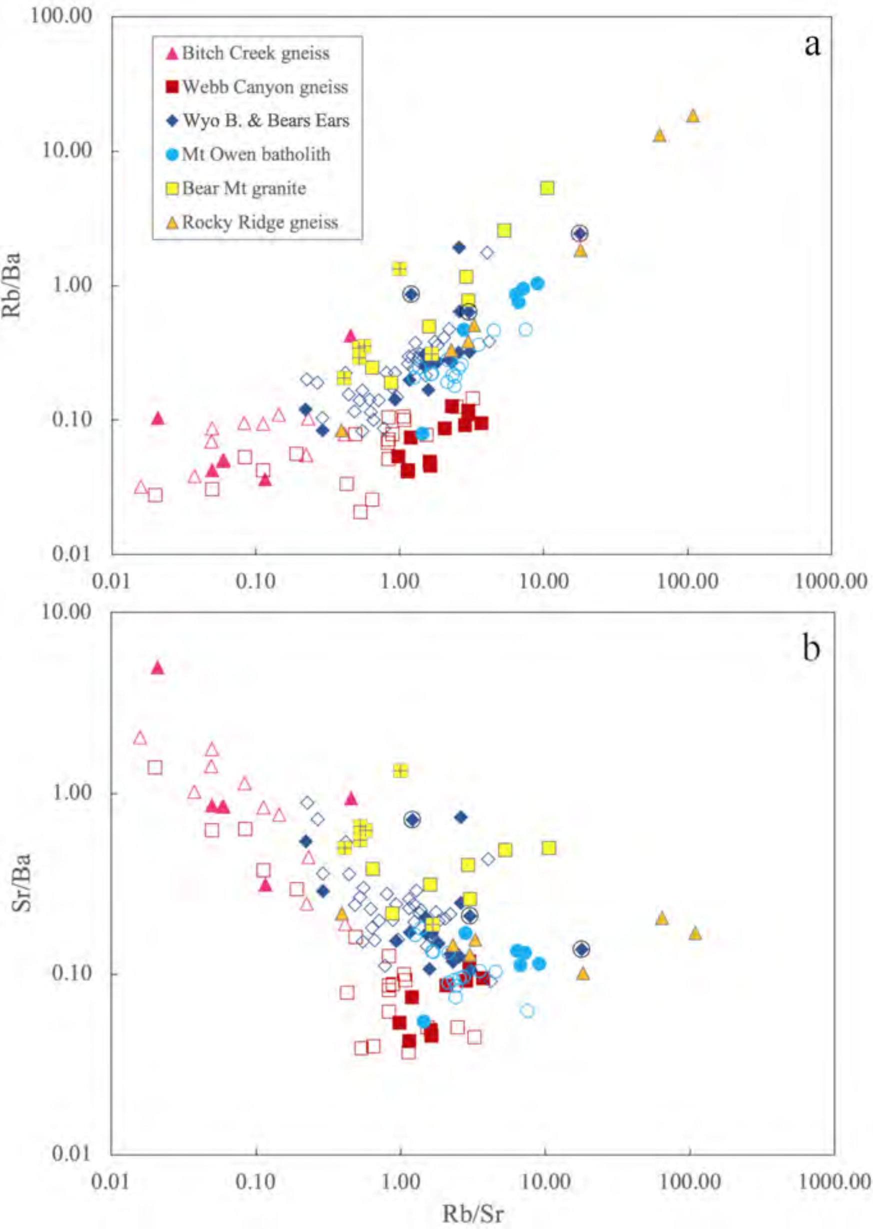
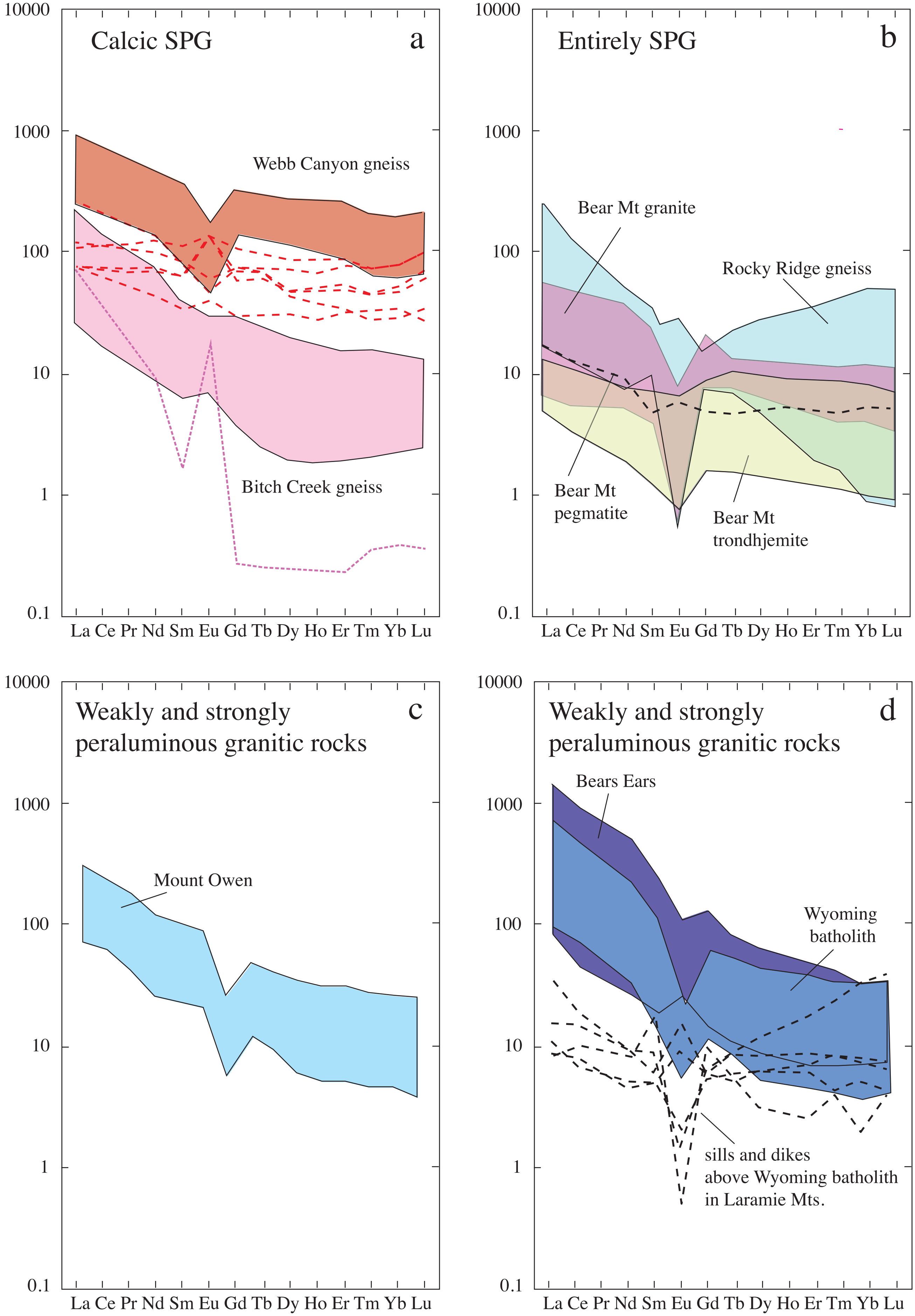
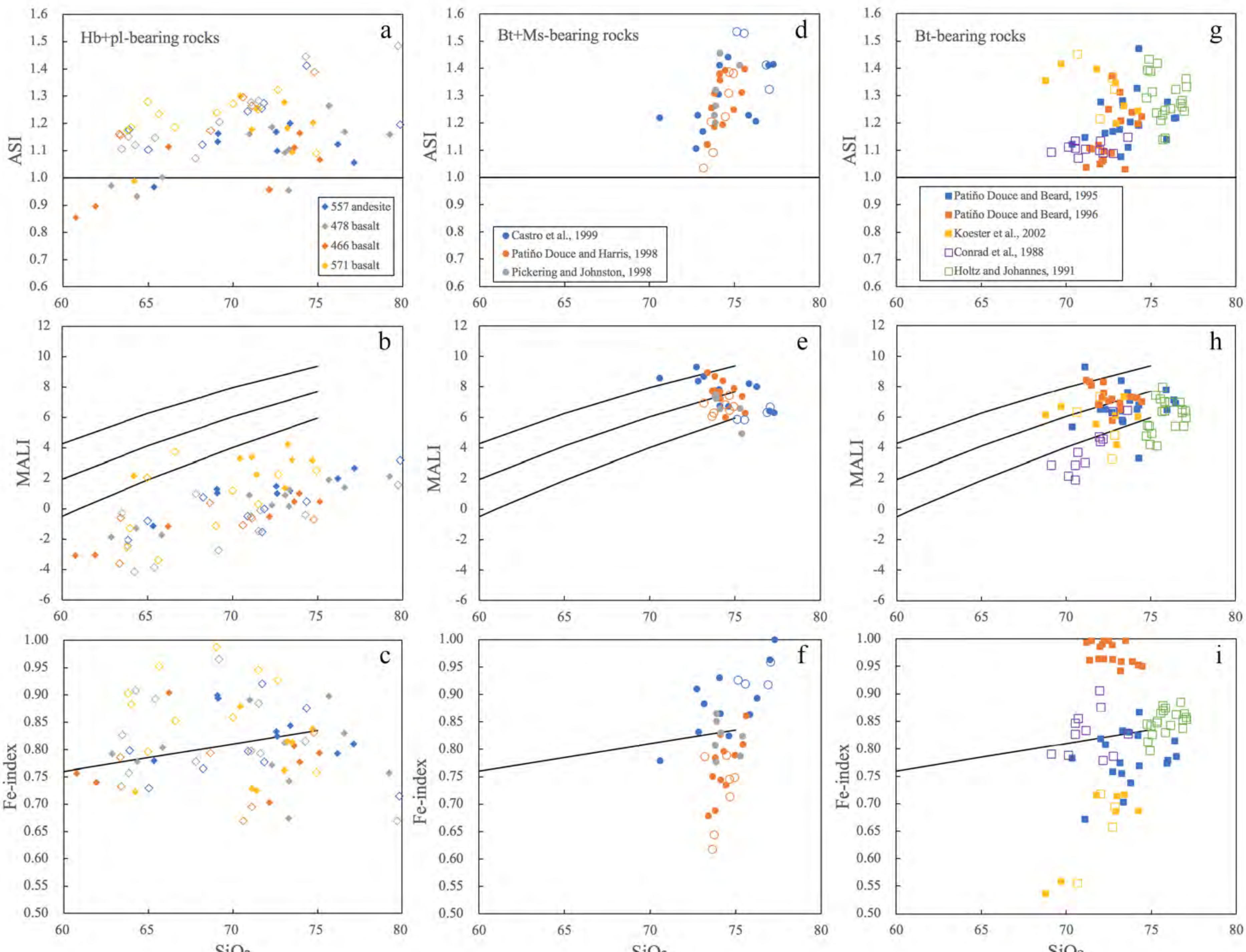

a
b
Bitch Creek gneiss
Webb Canyon gneiss
Wyo B. & Bears Ears
Mt Owen batholith
Bear Mt granite
Rocky Ridge gneiss
Rb/Ba
Sr/Ba
Rb/Sr
100.00
10.00
1.00
0.10
0.01
1000.00

Fig 7



10000
1000
100
10
1
0.1
Calcic SPG
a
Webb Canyon gneiss
Bitch Creek gneiss
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Entirely SPG
b
Bear Mt granite
Rocky Ridge gneiss
Bear Mt
pegmatite
Bear Mt
trondhjemite
Weakly and strongly
peraluminous granitic rocks
c
Mount Owen
d
Bears Ears
Wyoming
batholith
sills and dikes
above Wyoming batholith
in Laramie Mts.

Fig 8


Hb+pl-bearing rocks
a
557 andesite
478 basalt
466 basalt
571 basalt
ASI
b
MALI
c
Fe-index
SiO2
Bt+Ms-bearing rocks
d
Castro et al., 1999
Patiño Douce and Harris, 1998
Pickering and Johnston, 1998
e
f
Bt-bearing rocks
g
Patiño Douce and Beard, 1995
Patiño Douce and Beard, 1996
Koester et al., 2002
Conrad et al., 1988
Holtz and Johannes, 1991
h
i

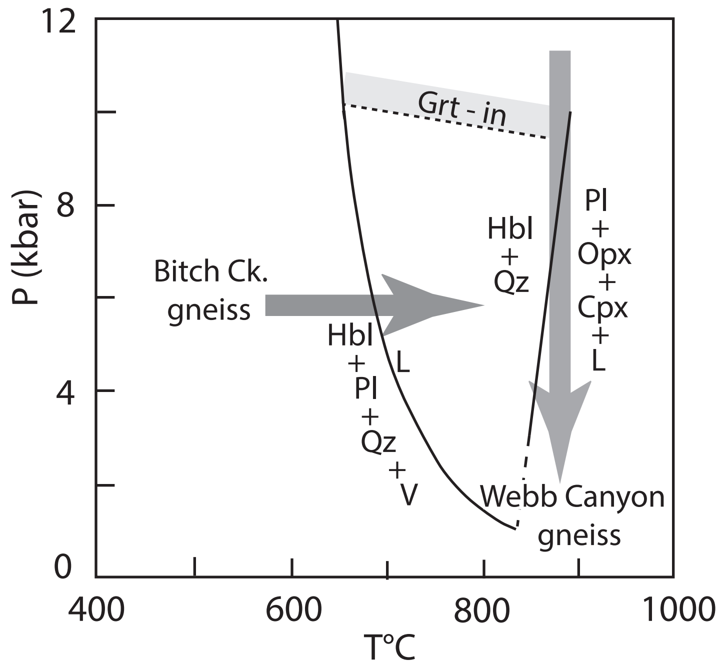
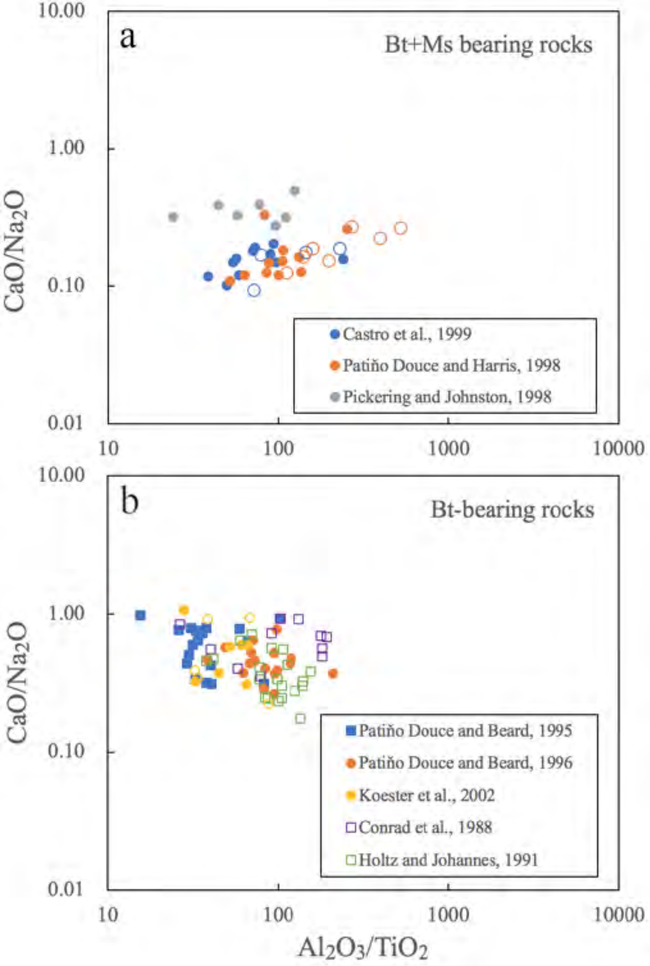

12
8
4
0
P (kbar)
400
600
800
1000
T°C
Grt - in
Bitch Ck.
gneiss
Hbl
+
Qz
Hbl
+
Pl
+
Qz
+
V
L
Pl
+
Opx
+
Cpx
+
L
Webb Canyon
gneiss

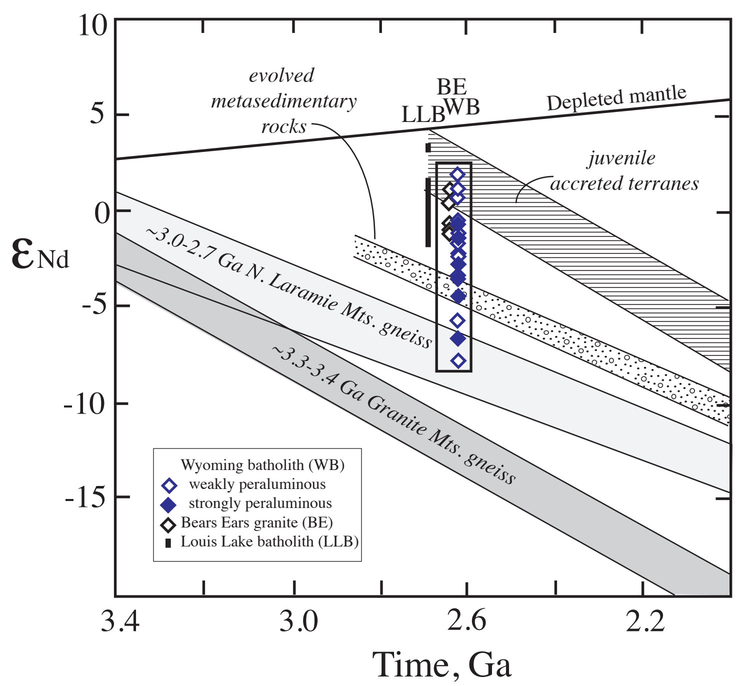
Fig 9

Fig 10



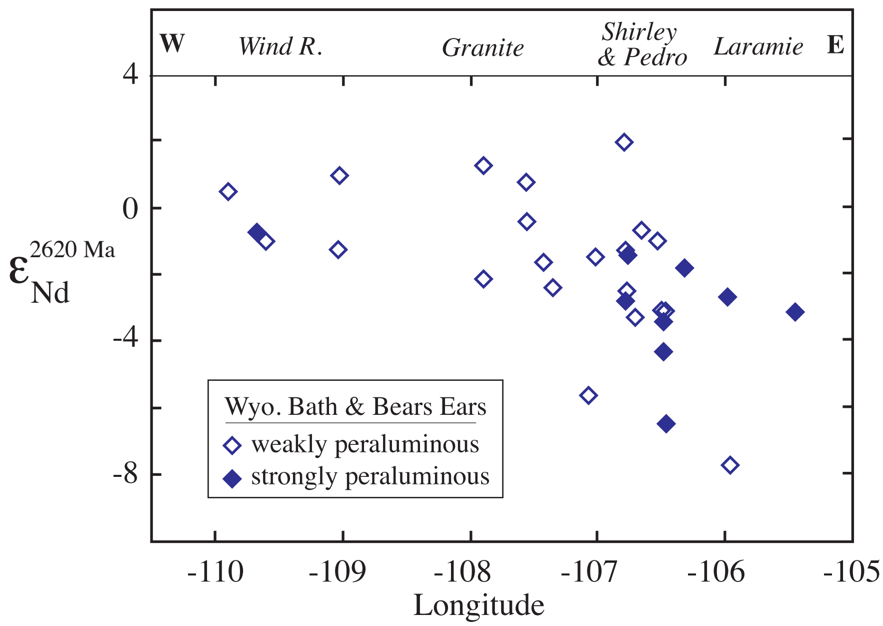
a
Bt+Ms bearing rocks
10.00
1.00
0.10
0.01
CaO/Na2O
10
100
1000
10000
Castro et al., 1999
Patiňo Douce and Harris, 1998
Pickering and Johnston, 1998
b
Bt-bearing rocks
Patiňo Douce and Beard, 1995
Patiňo Douce and Beard, 1996
Koester et al., 2002
Conrad et al., 1988
Holtz and Johannes, 1991
Al2O3/TiO2

Fig 11.



10
5
0
-5
-10
-15
εNd
3.4
3.0
2.6
2.2
Time, Ga
evolved
metasedimentary
rocks
BE
LLB
WB
Depleted mantle
juvenile
accreted terranes
~3.0-2.7 Ga N. Laramie Mts. gneiss
~3.3-3.4 Ga Granite Mts. gneiss
Wyoming batholith (WB)
weakly peraluminous
strongly peraluminous
Bears Ears granite (BE)
Louis Lake batholith (LLB)

Fig 12



W
Wind R.
Granite
Shirley & Pedro
Laramie
E
4
0
-4
-8
$\varepsilon_{Nd}^{2620 Ma}$
Wyo. Bath & Bears Ears
weakly peraluminous
strongly peraluminous
-110
-109
-108
-107
-106
-105
Longitude