Precambrian Research 228 (2013) 151–163

Contents lists available at SciVerse ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

Proterozoic ferroan feldspathic magmatism

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ARTICLE INFO

Article history:
Received 18 April 2012
Received in revised form 15 January 2013
Accepted 17 January 2013
Available online xxx

Keywords:
Ferroan granitoids
A-type
Proterozoic
Intraplate magmatism
Geochemistry
Petrogenesis

ABSTRACT

The Proterozoic eon is characterized by an unusual abundance of ferroan feldspathic rocks that range in composition from granite to quartz syenites to feldspathoid-bearing syenites. Three associations of ferroan rocks may be recognized on the basis of major element compositions: (1) metaluminous alkalic to alkali-calcic syenites and granites associated with anorthosites and iron-rich basaltic rocks; (2) alkaline intrusions in continental rifts; and (3) calc-alkalic metaluminous to peraluminous granitoid plutons that are less strongly ferroan than the other two groups. The first two groups form by differentiation of tholeiitic to alkali basaltic parental magmas; the third by partial melting of quartzo-feldspathic crust. Although all three associations may form in intraplate settings, only the alkaline intrusions, which typically contain high incompatible trace element abundances, plot entirely within the "within plate granite" fields on trace element discrimination diagrams. Processes of crustal melting and magma mixing have had a greater effect on the trace element compositions of ferroan granitoids from the other two associations, causing some rocks to plot outside this field.

Of these three associations, the granitoids associated with anorthosites are the most voluminous and are essentially restricted to the Proterozoic. Special conditions, perhaps related to the presence of a long-lived supercontinent under which widespread mantle upwelling took place, appear required to explain the abundance of these rocks. Ferroan alkaline rocks, although rarely preserved in Archean crust, are present in Proterozoic and Phanerozoic rifts. The earliest alkaline intrusions thus may mark the establishment of rigid continents capable of rifting. The formation of ferroan calc-alkalic granites does not appear to be time-dependent: these granites have been generated throughout Earth history in response to crustal melting.

1. Introduction

Ferroan magmatism is a characteristic feature of the Proterozoic eon. The end products of this magmatism are feldspathic rocks that are extremely enriched in FeO relative to MgO ($FeO/(FeO+MgO)>0.8$) and likewise are enriched in many incompatible trace elements, including REE (except Eu), Zr, Nb and Ta. These ferroan feldspathic rocks may range in composition from granite, through syenite, to feldspathoid-bearing syenites, depending on the composition of the source magma and the evolution path followed by the individual intrusions (Frost and Frost, 2011). They are found in three main associations. The first are metaluminous granites that are commonly associated with massif anorthosites and iron-rich basaltic rocks. The second are ferroan alkaline plutons that occur in small volumes, commonly in rift environments.[1] Finally, some Proterozoic ferroan granitoids are calc-alkalic, and range from metaluminous to peraluminous. They form by crustal melting in a variety of tectonic environments that produce crustal melts.

Although ferroan granitoids occur in the Archean, including the 2.78 Ga Gaborone complex (Moore et al., 1993), and in the 2.73–2.76 Ga Carajás province of Brazil (de Mesquita Barros et al., 2009; Feio et al., 2012), they are rare in the Archean compared to their great abundance in the Proterozoic. Ferroan granitoids also occur in the Phanerozoic, but the voluminous rapakivi granite intrusions common in the Proterozoic are rare, as are the anorthosite complexes with which they are commonly associated (Rämö and Haapala, 1995; Ashwal, 2010). Similarly, ferroan alkaline intrusions are rare in the Archean but become widespread in the Proterozoic and are well-represented throughout the

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[1] We use the term "alkaline" as defined by Shand (1922) to describe rocks in which the molecular ratio of Na + K to Al and Si is in excess of 1:1:6; that is, rocks for which either alumina or silica or both are deficient such that the rock contains higher alkalis than can be accommodated in feldspar alone.

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http://dx.doi.org/10.1016/j.precamres.2013.01.016

Phanerozoic (Blichert-Toft et al., 1996). In this paper we review the compositional characteristics of ferroan intraplate feldspathic magmas, their tectonic environments, and speculate on reasons for their relative prominence in the Proterozoic.

2. The nature of ferroan magmatism

Ferroan magmatism includes both silica-saturated and silica-undersaturated rock compositions (Frost and Frost, 2008). Most reviews of Proterozoic within-plate granitoids have focused on quartz-saturated granites and granodiorites (i.e., Anderson, 1983; Eby, 1990; Emslie, 1991; Rämö and Haapala, 1995). These granitoids have been referred to as "A-type", but this term has been applied to such a variety of rocks formed in various tectonic environments that we have recommended that it be discontinued (Frost and Frost, 2011). In this review we include silica-saturated and silica-undersaturated alkaline rocks as well as granitoids (Fig. 1) because by doing so we cover the entire compositional range of magmas intruded into Proterozoic terrains and can infer more completely the conditions that led to intracontinental magma genesis at that time. This wide variety of ferroan rocks ranges from quartz-saturated to quartz-undersaturated rocks, and from metaluminous and peraluminous to peralkaline rocks (Fig. 1 and Frost and Frost, 2008). We consider it important to include alkaline rocks in this discussion because peralkaline granites are recognized as part of the ferroan suite (Frost and Frost, 2011), and some ferroan batholiths, for example the Pikes Peak batholith (Barker et al., 1975) and the Sherman batholith (Frost et al., 1999), contain both metaluminous and peralkaline components. In addition, some nepheline syenite intrusions, such as Ilímaussaq (Bailey et al., 2001) and Puklen (Marks et al., 2003), contain minor amounts of peralkaline granite. Furthermore, it has long been recognized that basaltic magmatism ranging from strongly Q-normative tholeiites to Ne-normative basanites are common in intracratonic rifts (Williams, 1969; Anthony et al., 1992), although most rifts contain only a portion of this compositional spectrum.

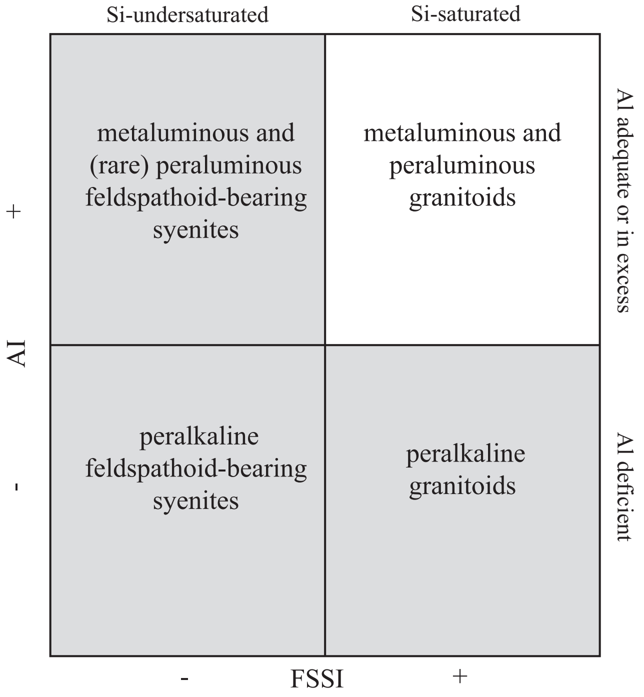

Fig. 1. AI vs. FSSI diagram (from Frost and Frost, 2008) showing the compositional range of ferroan plutons discussed in this paper. Shaded area is the field for alkaline intrusive rocks. AI, alkalinity index; where AI = Al − (K + Na) on a molecular basis. Peralkaline rocks have AI < 0 whereas metaluminous and peraluminous rocks have AI > 0. FSSI, feldspathoid silica-saturation index; where FSSI = normative Q − [Lc + 2(Ne + Kp)]/100. Silica-saturated rocks have FSSI > 0; silica-undersaturated rocks have FSSI < 0.

2.1. Compositional range of intraplate ferroan granitoids

Frost and Frost (2011) recognized eight types of ferroan granitoids that can be distinguished on the basis of major element chemistry. These include alkalic granitoids that may be metaluminous or peralkaline, alkali-calcic granitoids that may be metaluminous, peraluminous or peralkaline, calc-alkalic granitoids that may be metaluminous or peraluminous, and rare calcic ferroan granitoids.[2] These granitoids may form by two distinct end-member processes. Extreme differentiation of basaltic melts results in ferroan granitoids that are either peralkaline alkalic and alkali-calcic, or metaluminous alkalic, alkali-calcic, and calc-alkalic, with alkalinity increasing with increasing pressure of differentiation.[3] Partial melting of tonalitic to granodioritic crust produces alkali-calcic to calc-alkalic granitoids that are metaluminous at low pressures and peraluminous at high pressures. It is likely that most ferroan granitoids formed by a combination of these two processes (Frost and Frost, 2011).

2.2. Compositional range of intraplate ferroan syenites

In addition to granites, which by definition are over-saturated with respect to silica, Proterozoic feldspathic ferroan rocks may also include monzonites or syenites. Examples include syenites of the Klokken intrusion (Parsons, 1979, 1981) and silica-undersaturated nepheline syenites of the Ilímaussaq intrusion (Bailey et al., 2001). These rocks are typically alkalic according to the modified alkali lime index (MALI) of Frost et al. (2001a). They may be metaluminous or peralkaline, although some rare nepheline syenites are peraluminous (Vijaya Kumar et al., 2007). Differentiation of alkali basalts and basanites will lead to the formation of feldspathoid-bearing syenites. These syenites are likely to be metaluminous, unless the original magma had rather low abundances of normative anorthite, in which case the plagioclase effect (Bowen, 1945) could cause these feldspathoid-bearing syenites to be peralkaline. These rocks are ferroan because the strongly alkaline composition requires extreme differentiation of a melt and this differentiation naturally enriches the FeO/(FeO + MgO) ratio of a magma (Markl et al., 2010).

3. Three tectonic associations of Proterozoic ferroan magmas

Although ferroan magmatic suites are present in most Proterozoic terranes, it is particularly well-exposed and well-studied in seven magmatic provinces (Fig. 2). Interestingly, plutons in each province evince a distinctive chemical signature and none of the provinces contain the whole range of ferroan magmatism that is possible (Table 1). Presumably this compositional variability is a manifestation of slightly different tectonic environments for each district.

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[2] Calcic ferroan granites include the Red Hill dolerites in Tasmania (McDougall, 1962), and ca. 1.9 Ga arc tonalites from the Flin Flon-Glennie Complex of the Trans-Hudson orogeny, Canada that are associated with volcanic massive sulfide deposits (Whalen et al., 2007, submitted for publication).

[3] We note that ferroan alkali-calcic granitoids also may form by partial melting of tholeiite differentiates, such as ferrodiorites. The chemical signatures of these rocks, however, are likely to be the same as granites produced by extreme differentiation (Frost et al., 2002).

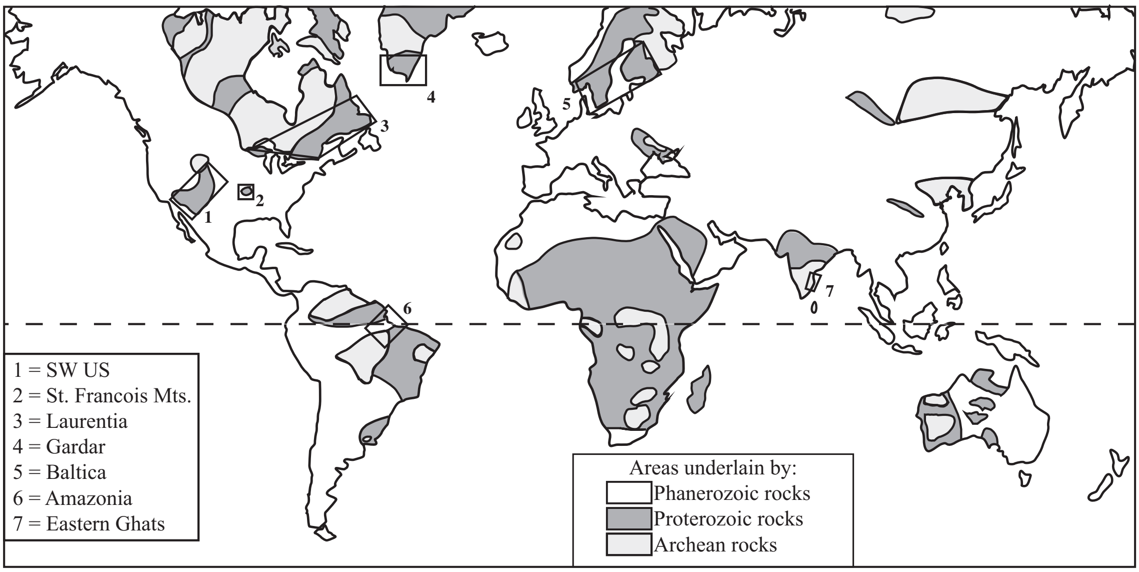

Fig. 2. Map of the world showing the distribution of Archean and Proterozoic rocks and the location of major Proterozoic igneous provinces.

Table 1
Major Proterozoic ferroan granitoid provinces.

Pluton	Composition	Age (Ga)	Reference
Southwestern U.S.			
Red Mtn	Alkalic metaluminous granitoids	1.43	Anderson et al. (2003)
Sherman	Alkali-calcic metaluminous granite	1.43	Frost et al. (1999)
Lincoln	Alkali-calcic peraluminous granite	1.43	Frost et al. (1999)
Pikes Peak	Alkali-calcic metaluminous granite	1.08	Barker et al. (1975) and Smith et al. (1999a,b)
Pikes Peak	Peralkaline alkali and alkali-calcic granite	1.08	Barker et al. (1975) and Smith et al. (1999a,b)
Holy Moses	Calc-alkalic metaluminous granite	1.33	Anderson and Bender (1989)
St. Vrain	Alkali-calcic peraluminous granite	~1.4	Gable (1985)
Saint Francois Mountains			
Munger	Alkali-calcic peraluminous rhyolites	1.45–1.48	Bickford et al. (1981)
Butler Hill	Calc-alkalic peraluminous rhyolites	1.45–1.48	Bickford et al. (1981)
Laurentia			
Flowers Bay	Alkalic metaluminous syenites alkalic peralkaline granite Alkali-calcic metaluminous granite	~1.2	Collerson (1982)
Lac de Brisson	Alkalic peralkaline granitoids	1.19	Pillet et al. (1992)
Kipawa	Metaluminous Ne-syenites to peralkaline granitoids	1.03	van Breeman and Currie (2004)
Cabonga	Peraluminous Ne-syenite	1.17	Hudon et al. (2003)
Gardar			
Klokken	Metaluminous to weakly peralkaline Q-syenites	1.16	Parsons (1979)
Puklen	Alkali-calcic peralkaline granitoids	1.2	Marks et al. (2003)
Ilímaussaq	Peralkaline Ne-syenites and minor peralkaline granite	1.16	Bailey et al. (2001)
Ivigtut	Alkali-calcic, metaluminous to peralkaline granitoids	1.1	Goodenough et al. (2000)
Motzfeldt	Metaluminous Ne-syenite and peralkaline Ne-syenites	1.28	Finch et al. (2001)
Baltica			
Wiborg	Alkali-calcic metaluminous to alkali-calcic peraluminous granites	1.63	Rämö and Haapala (2005)
Eurajoki	Alkali-calcic to calc-alkalic peraluminous granites	1.57	Haapala (1997)
Bjerkreim	Alkalic metaluminous granitoids	0.93	Duchesne and Wilmart (1997)
Amazonia			
Redenção	Alkali-calcic to calc-alkalic, metaluminous to peraluminous granites	~1.8	de Oliveira et al. (2009)
Musa	Calc-alkalic metaluminous granites	~1.8	Dall'Agnol et al. (1999)
Jamon	Calc-alkalic metaluminous to peraluminous granites	~1.8	Dall'Agnol et al. (1999)
Madeira	Alkalic metaluminous to calc-alkalic peralkaline granites	1.82	Costi et al. (2009)
Eastern Ghats			
Errakonda	Alkali-calcic to calc-alkalic, metaluminous to peralkaline granitoids	1.35	Vijaya Kumar et al. (2007)
Uppalapadu	Peraluminous Ne-syenites	1.35	Vijaya Kumar et al. (2007)
Elchuru	Metaluminous Ne-syenites	1.32	Upadhyay et al. (2006)

Below we discuss type examples of each of the three associations of intraplate ferroan magmatism: (1) the southwestern U.S. host numerous metaluminous granitoid plutons that are locally associated with massif anorthosites and iron-rich basaltic rocks, (2) the Gardar province exposes spectacular ferroan alkaline plutons in a rift environment, and (3) the Jamon suite intruding the Amazonia craton represent calc-alkalic metaluminous to peraluminous ferroan granites that form by crustal melting.

We focus on intrusive rocks because the level of erosion in Proterozoic terranes is commonly deep enough that the extrusive rocks are rarely preserved. However, there are extrusive equivalents of these ferroan rocks in places like the St. Francois Mountains of Missouri, USA, and these exhibit the same compositions – alkali-calcic trending to calc-alkalic at high silica, probably due to crustal assimilation (Table 1).

3.1. *Ferroan granitoids associated with anorthosites and iron-rich basaltic rocks*

The association of ferroan granitoids (granites, monzonites, and syenites) with massif anorthosites is well-known (Emslie, 1978). The plutons directly associated with massif anorthosites tend to be metaluminous alkalic to alkali-calcic (Frost et al., 2001a; Frost and Frost, 2008, 2011). Many ferroan plutons, such as the Pikes Peak (Barker et al., 1975) and the Wolf River batholith (Anderson and Cullers, 1978) are not associated with a massif anorthosite but contain inclusions of anorthosite. In most of the plutons in this group, such as the Sherman (Frost et al., 1999), Suomenniemi (Rämö, 1991) and the Nain Plutonic Suite (Emslie and Stirling, 1993) granitoids and ferrobasalts are coeval; felsic and mafic rocks occur together in composite dikes and exhibit various degrees of hybridization. As a result, the rocks of this group exhibit an exceptional range in silica contents. The most silica-poor portions of the suite are ferrodiorite and monzodiorite. These grade into monzonites and syenites and extend to true granites (Frost and Frost, 2011).

Generation of massif anorthosites and related rocks requires input of mantle heat and magma to the base of the crust, likely associated with a rising plume of asthenospheric mantle (Emslie et al., 1994; Frost and Frost, 1997). Tholeiitic basaltic magma emplaced near the base of the crust differentiates, producing a magma enriched in plagioclase and in iron relative to magnesium. Plagioclase cumulates may float and be emplaced diapirically to form anorthosite; the expelled liquid is parental to the syenitic and granitic rocks of the association (Longhi and Ashwal, 1985; Mitchell et al., 1996; Scoates et al., 1996).

The petrogenetic relationship of the ferroan granitoids to tholeiitic basaltic rocks is indicated by the low oxygen fugacity of the rocks (Frost and Frost, 1997), their low water contents, and their high magmatic temperature (>900 °C) (c.f. Creaser et al., 1991; Patiño Douce, 1997). At low silica the extraction of augite during fractionation will increase MALI in the residual magma. At higher silica contents, the MALI of a suite of rocks follows a trend with increasing silica that is dictated by the crystallization of feldspars. Once feldspars become important crystallizing phases, the residual melt will follow a trend sub parallel to the boundaries between the alkali – alkalic-calcic – calc-alkalic – calcic fields (Frost and Frost, 2008). Because increasing pressure favors crystallization of clinopyroxene at the expense of plagioclase (Fram and Longhi, 1992; Scoates and Lindsley, 2000; Whitaker et al., 2007), the MALI of a suite of ferroan granites reflects the pressure of differentiation. Extremely low-pressure differentiation can produce ferroan calcic metaluminous granites, whereas differentiation at mid-crustal depths will produce ferroan alkalic metaluminous granites (Frost and Frost, 2011).

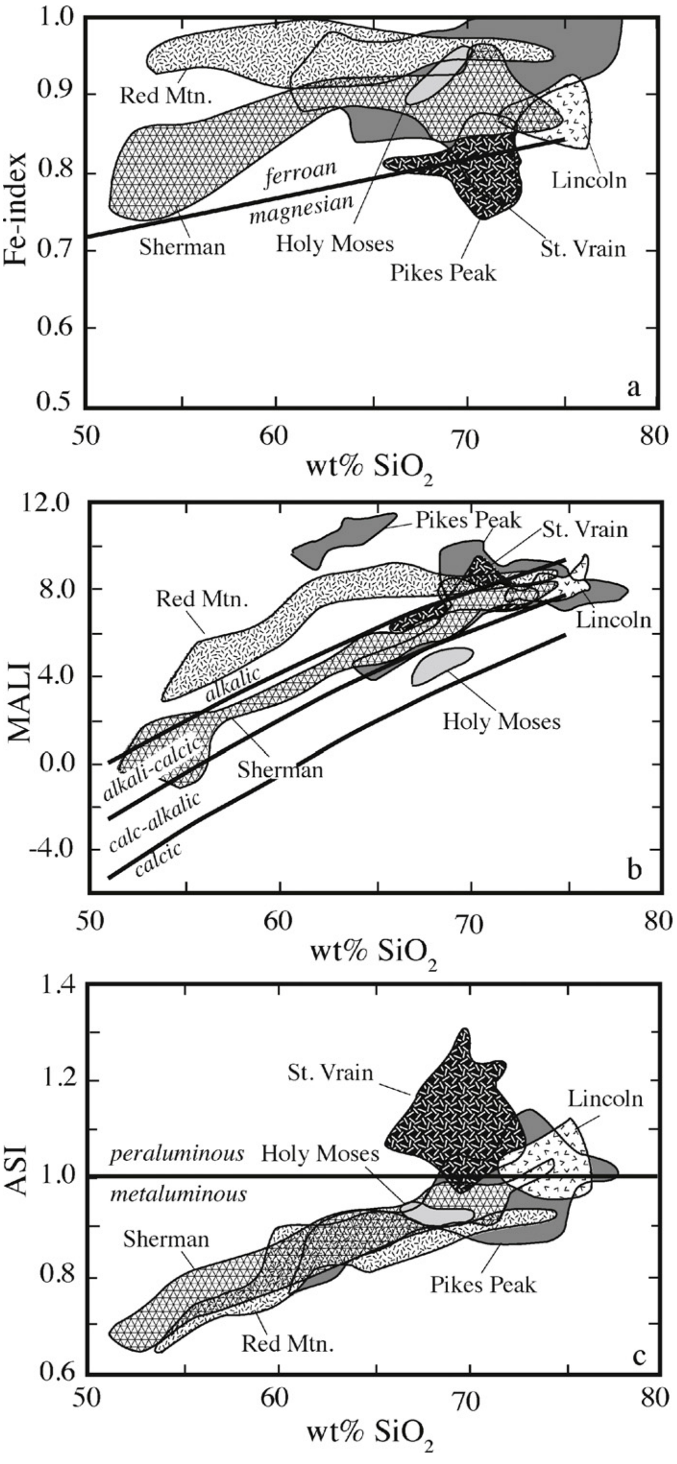

Fig. 3. Major element variation diagrams showing the range of compositions for granitoids from the southwestern U.S. (a) Fe-index, $FeO^{total}/FeO^{total} + MgO$. (b) Modified alkali lime index (MALI), $Na_2O + K_2O - CaO$. (c) Aluminum saturation index (ASI), molecular $Al/Ca - 1.67P + Na + K5$. Boundaries between ferroan and magnesian and alkalic, alkali-calcic, calc-alkalic, and calcic granitoids from Frost et al. (2001a) and Frost and Frost (2008). Sources for data are given in Table 1.

3.2. *Ferroan alkaline plutons*

The rocks of the ferroan alkaline association are among the most strongly ferroan magmas known. This group includes both silica-undersaturated feldspathoid-bearing syenites and peralkaline granites. The distinction between this group of ferroan plutons and the previous one is somewhat artificial because some alkaline provinces, such as the Gardar (Upton et al., 2003) and Eastern Ghats (Vijaya Kumar et al., 2007), contain anorthosite. However, in general, the provinces containing abundant rapakivi granites and massif anorthosite lack alkaline intrusions. Only small amounts of peralkaline granite are associated with the Pikes Peak and Sherman batholiths (Smith et al., 1999a,b; Frost et al., 1999).

Ferroan alkaline rocks are associated with continental rifts, modern examples occurring in the East African rift system (Bailey, 1992). Like the ferroan granitoids associated with anorthosite, ferroan alkaline plutons may form by extreme differentiation of basaltic magma, the major difference being that the parent basalt is alkali basalt, rather than tholeiite (Mitchell and Platt, 1982).

3.3. *Ferroan calc-alkalic plutons*

Ferroan calc-alkalic plutons are not associated with anorthosite magmatism and are rarely associated with mafic magmatism of any kind. They are metaluminous to peraluminous and are distinctly less iron-enriched than plutons associated with the other two groups. This type of rock may form in any tectonic environment that produces partial melts of granodioritic or tonalitic crustal rocks. Experimental studies show that partial melting of tonalite to granodiorite can produce high-silica, calc-alkalic melts (Skjerlie and Johnston, 1993; Patiño Douce, 1997). At low pressure this melting produces metaluminous to slightly peraluminous ferroan compositions, whereas melting at higher pressures produces strongly peraluminous melts (Frost and Frost, 2011). These types of plutons are compositionally distinct from most of the metaluminous granitoids associated with anorthositic rocks. They tend to be more magnesian, more calcic, and peraluminous. However, some of the granitoids that are temporally associated with anorthositic rocks, such as the Holy Moses granite (Fig. 3) may have assimilated enough crustal material to make them compositionally indistinguishable from ferroan calc-alkalic plutons.

4. Examples of ferroan magmatic provinces

4.1. *Southwestern U.S.*

1.6–1.3 Ga ferroan granites compose approximately 20% of Proterozoic outcrop in the southwestern U.S. (Frost et al., 2001b). They include alkalic and alkali-calcic metaluminous granites, which have been referred to as rapakivi granites (Rämö and Haapala, 1995) or ilmenite granites (Anderson and Morrison, 2005). Examples of this type of ferroan granitoid are the Red Mountain and Sherman intrusions associated with the Laramie Anorthosite Complex in Wyoming, and the Pikes Peak batholith of Colorado (Fig. 3). Other granites in this province are calc-alkalic and metaluminous, such as the Holy Moses granite of Arizona (Anderson and Bender, 1989). These commonly contain magnetite and are less potassic and less ferroan than many alkalic and alkali-calcic metaluminous plutons. A third group of intrusions extend to peraluminous compositions, such as the Lincoln granite in the Sherman batholith (Frost et al., 1999) and the St. Vrain granite of northern Colorado (Gable, 1985). These and other peraluminous granites extend from Colorado to New Mexico and Arizona (Anderson and Morrison, 2005); they are less iron-rich than the other Proterozoic granites in this region (Fig. 3).

Most ferroan granites of the southwestern U.S. plot within the within-plate granite or “A-type” granite fields on trace element variation diagrams (Fig. 4). Some suites, such as the Pikes Peak and

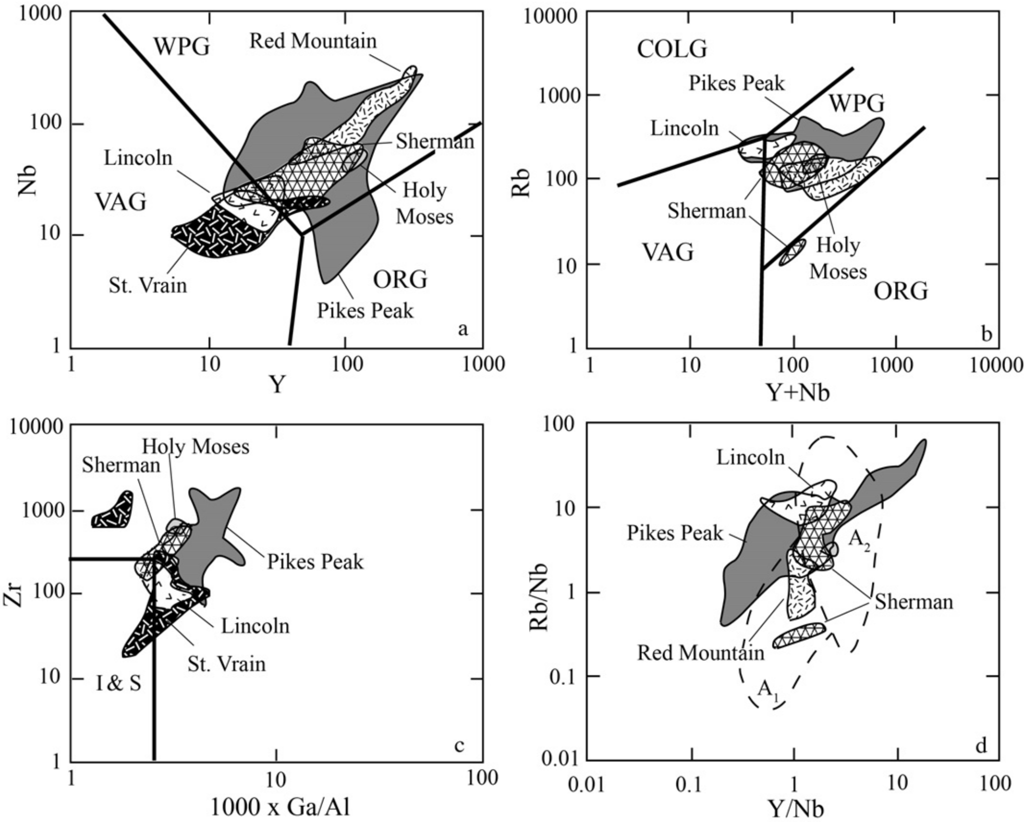

Fig. 4. Trace element discrimination diagrams showing the trends for granitoids from the southwestern U.S. (a) Nb vs. Y, (b) Rb vs. Y + Nb, (c) Zr vs. 1000 × Ga/Al, (d) Rb/Nb vs. Y/Nb. Boundaries on these diagrams after Pearce et al. (1984), Whalen et al. (1987), and Eby (1992). Sources for data are given in Table 1.

Sherman batholiths, encompass a large range of compositions on these diagrams. In some suites, such as the Red Mountain pluton, this range of trace element compositions is produced by fractional crystallization (c.f. the fractional crystallization trends calculated by Pearce et al., 1984). For other intrusions, such as the Sherman granite, similarly linear trends result from magma mixing of felsic with mafic magmas (c.f. Frost et al., 1999). The peraluminous St. Vrain and Lincoln suites extend from the within-plate field into the volcanic arc field (Fig. 4a and c) or from the "A-type" to the I and S granite field (Fig. 4b). The southwestern U.S. granites span the "A1" and "A2" subfields on the Y/Nb diagrams of Eby (1992), and many rocks, especially from the Pikes Peak batholith lie outside of either field. The range in Y/Nb probably reflects crustal contamination of magmas because continental crust tends to have Y/Nb > 1 (Eby, 1992).

Nd, Sr, and Pb isotopic studies indicate that the ferroan granites of the southwest U.S. have originated from differentiated tholeiitic basalt that has assimilated varying amounts of crustal material (Frost et al., 1999, 2001b, 2002; Anderson et al., 2003; Anderson and Morrison, 2005). The most ferroan and alkalic of the suites, the Red Mountain pluton, shows very little evidence for crustal assimilation except in the most siliceous granites, and formed directly from differentiation of melts related to the Laramie Anorthosite Complex (Anderson et al., 2003). The northern Sherman granite experienced larger amounts of crustal assimilation (up to 40%; Frost et al., 2002). Crustal assimilation tends to drive magmas from strongly ferroan and alkalic to more calcic and magnesian compositions, as well as making them peraluminous. Oxygen isotopes also have documented that increasing crustal assimilation drives magmas to more peraluminous compositions because the more peraluminous intrusions have higher δ^{18}O (Anderson and Morrison, 2005).

4.2. Gardar province

The Gardar province of south Greenland was one of the provinces that Loiselle and Wones (1979) used to define A-type granites. It consists of a series of 1.1–1.3 Ga ferroan granites, syenites, and nepheline syenites, which are commonly peralkaline, and related rocks. A distinctive feature of the Gardar province is that some of the ferroan granites and syenites were emplaced into coeval syn-rift sediments and volcanic flows, clearly indicating the tectonic environment for this magmatism (Halama et al., 2003).

The rocks from the Gardar province are exceedingly enriched in iron. Fe-indices in excess of 0.90 are not uncommon; in many samples they reach nearly to 1.0 (Fig. 5a). The Gardar is a highly alkaline province (Fig. 5b); it hosts the Ilímaussaq intrusion, one of the most alkaline intrusions on Earth. The plutons in the Gardar province display the magmatic processes that lead to the wide variety of rock types. The Klokken intrusion, a gabbro that grades into a layered syenite (Parsons, 1979), is a good example of a pluton that formed by simple differentiation. Rocks from the pluton from a linear array on a MALI diagram that is subparallel to the alkalic – alkali-calcic boundary; a trend that reflects control by plagioclase fractionation (Frost and Frost, 2008). This is also seen in Fig. 5c, where Klokken forms a linear trend that shows increasing alkalinity with increasing differentiation. Frost and Frost (2008) argue that this reflects Bowen's (1945) "plagioclase effect", whereby the crystallization of a calcic plagioclase will deplete the residual melt in aluminum while enriching it in sodium.

The nepheline syenites from the Gadar, as exemplified by Ilímaussaq and Moztfeldt, lie at extreme values of MALI (Fig. 5b). This could have been caused by simple differentiation, because increases in nepheline abundance will drive the MALI index to higher values while decreasing silica content. However, the broad range in values along with other evidence suggests that processes such as interaction with alkaline fluids are responsible for some of the enrichment in MALI for the Ilímaussaq (Schönenberger et al., 2006).

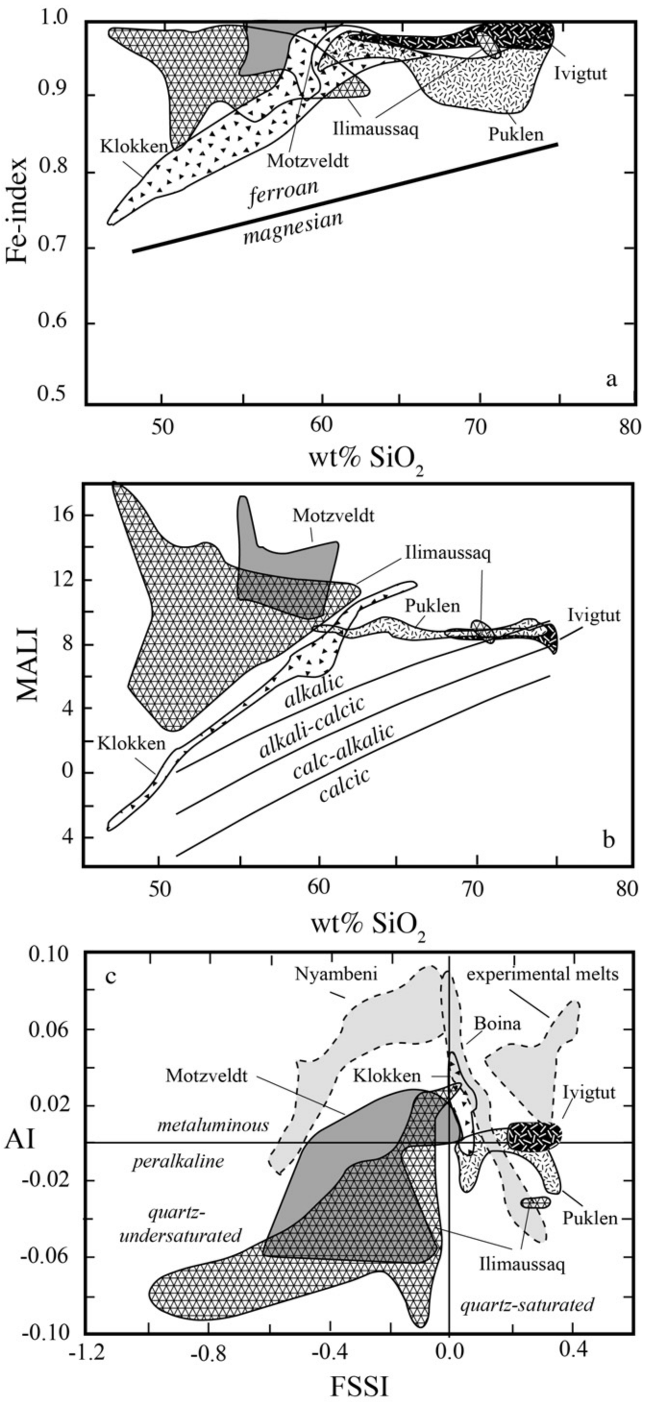

Fig. 5. Major element variation diagrams showing the range of compositions for felsic rocks from the Gardar province. (a) Fe-index, (b) MALI, (c) AI vs. FSSI. Boundaries are from Frost et al. (2001a) and Frost and Frost (2008). Sources of data are given in Table 1.

The peralkaline granites of the Gardar province, represented in our study by Ivigtut and the peralkaline granites of the Ilímaussaq and Puklen intrusions, appear to result from crustal assimilation by alkaline melts (Marks et al., 2003). This is seen on the MALI diagram by the linear array that Puklen and Ivigtut form, with increasing silica at nearly constant MALI (Fig. 5b). This is also recognized in Fig. 5c where the alkaline granites of the Gardar province lie between the fields outlined by the differentiation trends of alkaline volcanic

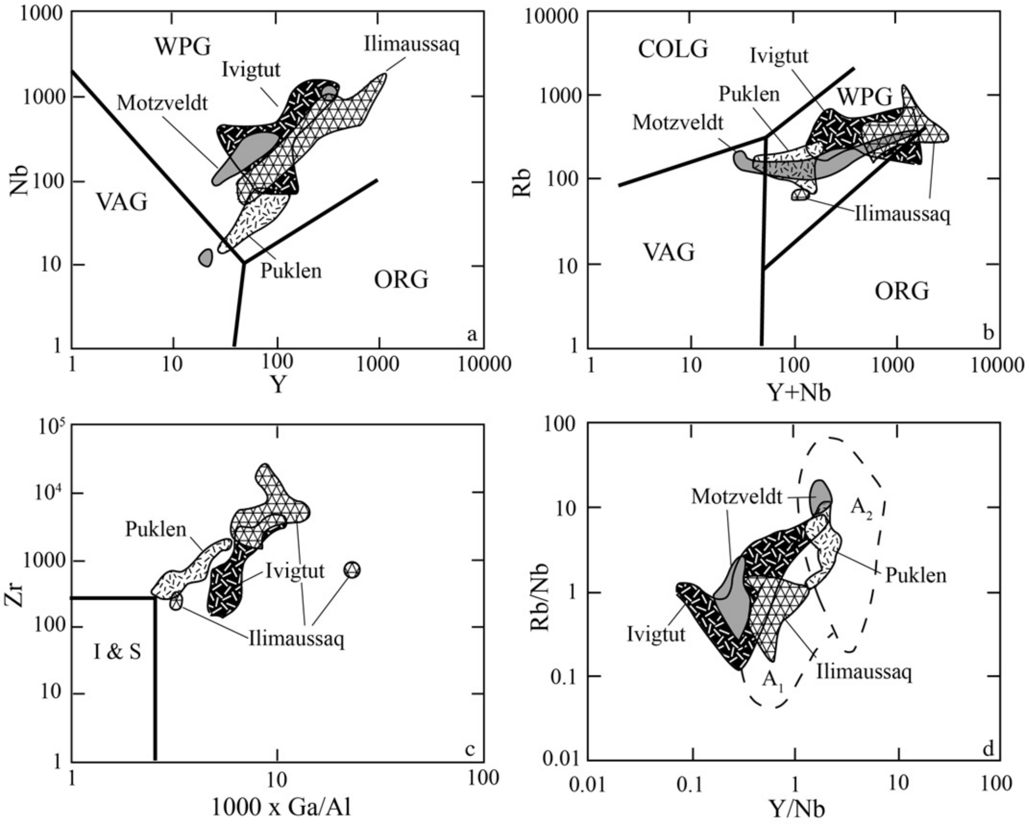

Fig. 6. Trace element discrimination diagrams showing the trends for granitoids from the Gardar province. (a) Nb vs. Y, (b) Rb vs. Y + Nb, (c) Zr vs. 1000 × Ga/Al, (d) Rb/Nb vs. Y/Nb. Boundaries are from Pearce et al. (1984), Whalen et al. (1987), and Eby (1992). Data for Boina, Nyambeni, and experimental melts are from Barberi et al. (1975), Bogaerts et al. (2006), Brotzu et al. (1983), Patiño Douce (1997), and Skjerlie and Johnston (1993). Other data sources are listed in Table 1.

rocks such as Nyambeni and Boina and the field of experimental crustal melts.

The Gardar intrusions are characterized by high incompatible trace element abundances, particularly for Zr, Y, and Nb (Fig. 6a–e). The granitoids fall in within-plate granite field of Pearce et al. (1984). On Rb/Nb v Y/Nb and diagram (Eby, 1992), Puklen and the falls in the "A_2" field, Ivigtut, other Motzvelt samples, and Ilímaussaq fall in the "A_1" field.

Neodymium and oxygen isotopic data from mineral separates from the Ilímaussaq and Motzfeldt intrusions indicates that the magmas are derived from a mantle source (Marks et al., 2004; Schönenberger and Markl, 2008). The less radiogenic Nd isotopic compositions of Ilímaussaq peralkaline granite suggest that this unit was formed by limited contamination of the mantle-derived melt by lower crustal rocks (Marks et al., 2004). Hydrogen isotopic data support interaction with late-stage fluids from a variety of sources (Marks et al., 2004; Schönenberger and Markl, 2008).

4.3. Amazonia

The 1.8 Ga plutons of the Jamon suite in the Amazonia craton are examples of ferroan granites that have been produced by melting of crustal rocks (de Oliveira et al., 2009). Characteristic features of these rocks are relatively magnesian composition compared to the ferroan granites associated with anorthosites. In addition these granites have calc-alkalic metaluminous to peraluminous compositions (Fig. 7). Unlike other groups of ferroan granitoids, these plutons lack low-silica members; most calc-alkalic ferroan granitoids have high silica contents (>70% SiO_2; Fig. 7).

Amazonian plutons cluster fairly tightly on trace element diagrams. However, as with granitoids from the southwestern U.S. that contain considerable crustal components, some rocks from these suites do not plot in the within-plate granite field or the "A-type" granite fields in Fig. 8, but extend into the volcanic-arc and I and S type granite fields.

Initial Nd isotopic compositions of the Jamon suite are strongly unradiogenic (Dall'Agnol et al., 1999; Rämö et al., 2002; Teixeira et al., 2002; Dall'Agnol et al., 2005). Initial ε_{Nd} at 1.88 Ga in the range of −8 to −12 have been interpreted to suggest that the granites were derived by partial melting of several isotopically-distinct Archean crustal sources (Dall'Agnol et al., 2005; de Oliveira et al., 2009).

5. Discussion

5.1. Usefulness of trace element discrimination diagrams

The descriptor "within-plate" is commonly applied to rocks with particular trace element compositions, using tectonic discrimination diagrams introduced by Pearce et al. (1984). A number of Proterozoic ferroan rock suites fall in multiple fields on trace element discrimination diagrams. Examples include St. Vrain, Sherman and Pikes Peak from the southwestern U.S. province (Fig. 4), and Musa and Bannach and Jamon from Amazonia (Fig. 8). The suites plot in multiple fields for a number of reasons. The fields on these diagrams reflect the sources of the magmas as well as the various processes that act upon the sources, such as enrichment by subduction-related fluids or underthrust continental crust and crustal interaction (Pearce, 1996). Depending upon the exact composition of the mantle and crustal sources, a particular suite may occupy different parts of a particular discrimination diagram. The location of granitic rock suites on these trace element diagrams is complicated by the fact that, unlike in basalts, trace elements in granitic rocks commonly are not incompatible

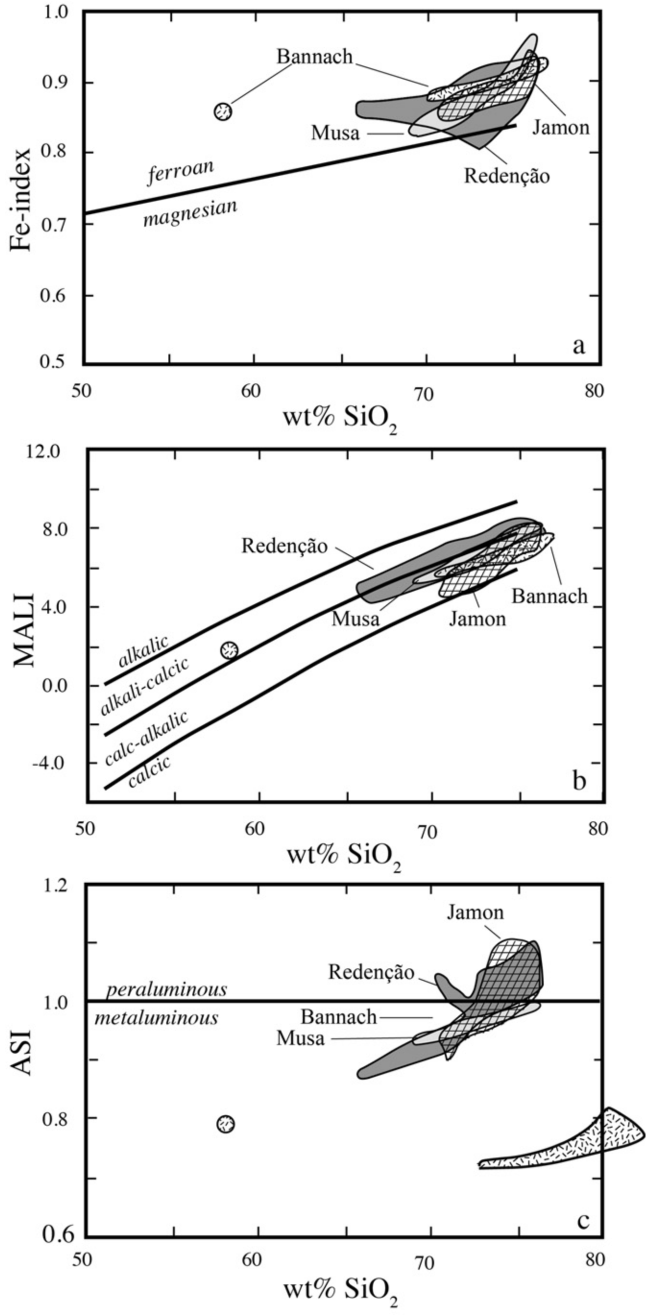

Fig. 7. Major element variation diagrams showing the compositional range of granitoids from the Amazonia province. Boundaries as defined by Frost et al. (2001a) and Frost and Frost (2008). Sources of data are given in Table 1.

(Bea, 1996). Elements such as REEs, U, Th, and Zr reside in minor mineral phases such as apatite, zircon, titanite, allanite and monazite. Other trace elements, including Nb and Y, are concentrated in oxides and amphiboles, among other minerals. As a result, the abundance of trace elements in granitoids, in addition to reflecting the composition of the parent magma, may also be strongly affected by the crystallization history of the magma and intensive parameters, particularly oxygen and water fugacity. In addition, crustal assimilation also may have a much larger influence on the trace element abundances of a felsic melt than on its major element compositions.

For example, the extension of the Sherman, St. Vrain and Pikes Peak compositions from the within-plate to the volcanic arc field reflects contamination with low Nb, low Y, crustal melts. On the other hand, the Gardar province plutons are highly enriched in incompatible trace elements and thus crustal contamination has a modest effect on their trace element compositions. These plutons plot almost exclusively in the within-plate field. We conclude that the identification of tectonic setting from trace element compositions is complicated in plutons that formed by multiple processes, including crystal accumulation, crustal contamination, and those originating from varying source regions (Pearce et al., 1984).

5.2. Size of Proterozoic ferroan plutons

Ferroan granite plutons are characterized by a wide range in size. The largest intrusions are the metaluminous granitoids associated with anorthosites. Because the exposures of granitoids in the southwestern U.S. are mostly fault-bounded, it is difficult to assess their areal extents but both the Pikes Peak and Sherman batholiths are at least 100 km wide in their maximum dimensions (Barker et al., 1975; Frost et al., 1999). An example of a batholith from this association that is not truncated by faults is the Wiborg batholith, which is at least 300 km in the largest dimension and is estimated to occupy 18,000 km^2 (Fig. 9; Rämö and Haapala, 2005; Rämö et al., 2010). The Amazonian plutons tend to be much smaller (Fig. 9). The largest ferroan calc-alkalic Amazonian pluton, Seringa, is about 60 km in the largest dimension (approximately 2000 km^2); the others are 10–40 km in diameter (de Oliveira et al., 2009). This size is similar to the Phanerozoic Lachlan ferroan calc-alkalic granites, most of which are 10 km or less in their maximum dimension (Collins et al., 1982). The ferroan alkaline intrusions of the Gardar and Eastern Ghats provinces are even smaller; few exceed 10 km in maximum dimension.

The size of the ferroan plutons probably reflects differences in the flux of heat into the crust during the formation of the various igneous provinces. This suggests that the flux of mantle heat is greatest in the broad belts that produced massif anorthosite and associated metaluminous granites, where approximately 20% of the exposed Precambrian crust is occupied by ferroan granites (Frost et al., 2001b; Vaasjoki et al., 2005). The heat flux is more focused in narrower rifts such as Gardar, where much smaller volumes of ferroan magma were emplaced. Ferroan plutons formed by crustal melting also tend to be small because only small degrees of melting will produce ferroan melts; higher degrees of melting will make magnesian melts (Skjerlie and Johnston, 1993).

6. Conclusions: abundance of ferroan magmatism throughout geologic time

In the introduction we observed that ferroan rocks are relatively rare in the Archean. This is a first-order geologic observation that carries important implications about crustal evolution. Most feldspathic ferroan magmatism is continental; only small volumes of ferroan rhyolites are found in oceanic settings (Bonin, 2007). One might conclude, therefore, that the rarity of extensive ferroan magmatism in the Archean reflects the temporal evolution of the continental crust, and that continental plates had not developed characteristics that are necessary to give rise to ferroan magmas in the early stages of Earth history.

However, if one examines the geologic record in more detail, it is clear that ferroan granites are not completely absent from the Archean rock record. Although ferroan granites associated with massif-type anorthosites occur almost exclusively in the Proterozoic, particularly in the Mesoproterozoic (Ashwal, 2010), and ferroan alkaline rocks likewise are uncommon (Blichert-Toft et al., 1996), ferroan calc-alkalic granitoids do occur in the Archean as well as later in Earth history (for example, the Neoarchean Planalto suite and Carajás A-type granites of Amazonia (Feio et al., 2012;

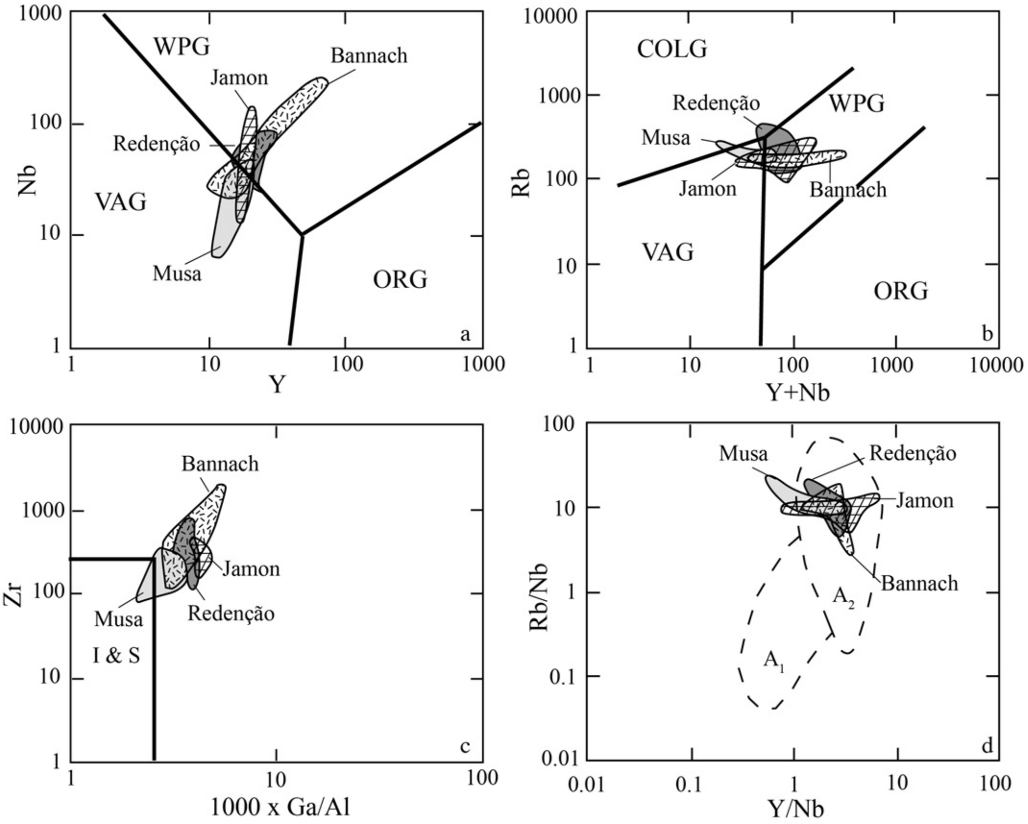

Fig. 8. Trace element discrimination diagrams showing the trends for granitoids from the Amazonia province. (a) Nb vs. Y, (b) Rb vs. Y + Nb, (c) Zr vs. 1000 × Ga/Al, (d) Rb/Nb vs. Y/Nb. Boundaries on these diagrams are from Pearce et al. (1984), Whalen et al. (1987), and Eby (1992). Sources for data are given in Table 1.

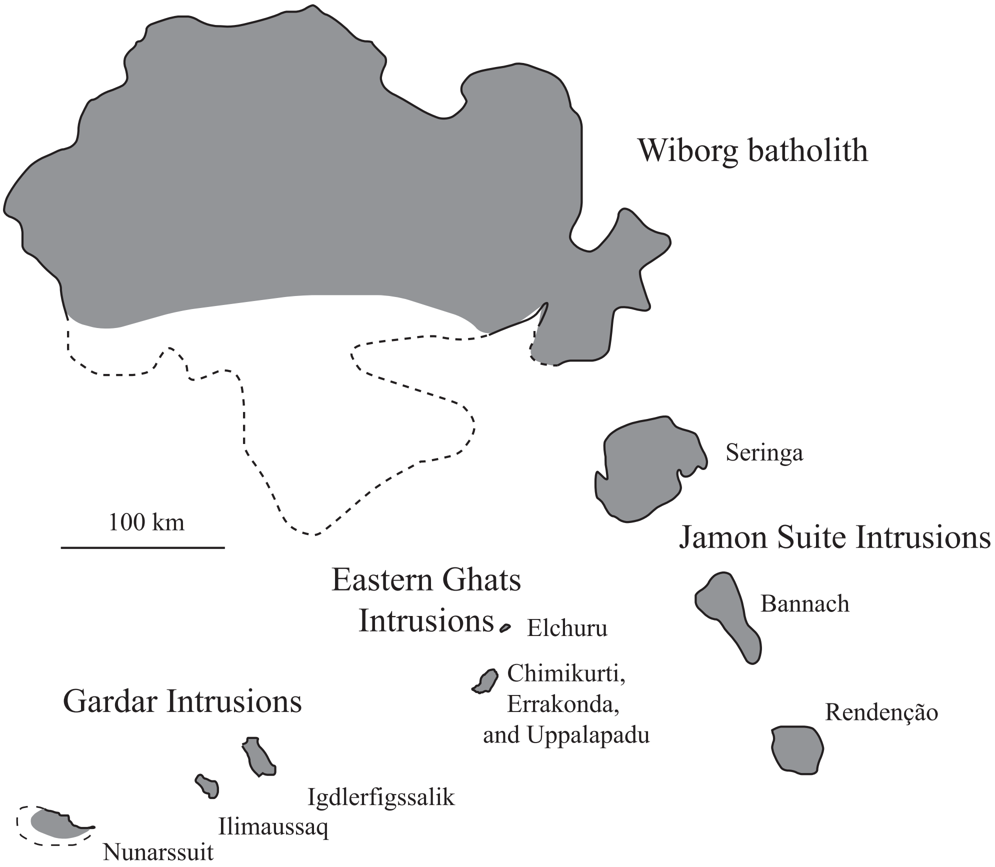

Fig. 9. Diagram comparing the sizes of various Proterozoic intraplate intrusions. Unshaded portion of the Wiborg batholith is the portion that lies beneath the Baltic Sea. *Source*: Data from Rämö and Haapala (2005), Vijaya Kumar et al. (2007), and de Oliveira et al. (2009).

Table 2
Compilation of age and estimated areal extent of ferroan granitoids associated with massif anorthosite complexes.

Name	Location	Estimated areal extent (km^2)	Age (Ma)	Reference
Fennoscandia				
Ragunda	Sweden	360	1514 ± 5	Persson (1999)
Salmi	Karelia, Russia	2700	1547–1530	Neymark et al. (1994)
Laitila	Finland	~300	1570–1540	Haapala (1997)
Åland	Finland	~300	1576–1568	Rämö (1991)
Nordingra	Sweden	~300	1578 ± 17	Persson (1999)
Riga	Latvia/Estonia	<57,500	1584 ± 7	Kirs et al. (2004)
Wiborg	Finland	18,000	1646–1615	Heinonen (2010)
Suomenniemi	Finland	365	1640–1635	Rämö (1991)
Ahvenisto	Finland	245	1642–1636	Heinonen and Rämö (2010)
Korosten	Ukraine	9000	1789 ± 2	Amelin et al. (1994)
Eastern North America				
St. Urbain	Quebec	~1000	1053 ± 3	Morrisett et al. (2009)
Lac Allard	Quebec	~1000	1148	Morrisett et al. (2009)
Adirondacks	New York	~5400	1154 ± 6	Chiarenzelli and McLelland (1991)
Morin	Quebec	~2500	1155 ± 3	Doig (1991)
Lac St. Jean	Quebec	~500	1156 ± 2	Hebert and van Breeman (2004)
Nain	Labrador	13,000	1.29–1.32	Ryan (2000) and Ashwal (2010)
Riviere-Pentecote	Quebec	~200	1354 ± 3	Hegner et al. (2010)
Harp Lake	Labrador	~500	1460	Hegner et al. (2010)
Mealy Mts	Labrador	~2500	1632 ± 3	Hegner et al. (2010)
Central and western North America				
Pikes Peak	Colorado	3100	1086 ± 3	Smith et al. (1999b)
San Gabriel	California	<250	1125	Carter (1980)
Laramie	Wyoming	>1300	1433 ± 2	Frost et al. (1999)
Wolf River	Wisconsin	4400	1485 ± 15	Anderson and Cullers (1978)
Horse Creek	Wyoming	>42	1771 ± 3	Frost et al. (2000)
South America				
Mucajaí complex	Brazil	2250	1540	Fraga et al. (2009)
Asia				
Damiao	China	~50	1740 ± 14	Zhao et al. (2009)
Africa				
Gabarone	Botswana	6000	2784 ± 1	Moore et al. (1993)

Notes: Ferroan granitoid occurrences listed are based upon a compilation by Rämö and Haapala (1995). Areal extents are estimates only: most intrusions are incompletely exposed and have faulted or covered margins. Some estimates are restricted to exposed outcrop area (for example Sherman) and others include estimated subsurface extent (for example, Wiborg and Riga). The size of the granitoid occurrence depends upon whether it is a complex of intrusions (Nain) or an individual pluton (Horse Creek). Identification of the feldspathic rocks that are petrogenetically related to a particular complex varies by investigator, leading to additional uncertainty. Nevertheless, it is clear that ferroan granitoids associated with anorthosite and related iron-rich mafic rocks are most abundant in the Paleo- and Mesoproterozoic, and include many sizable intrusions.

de Mesquita Barros et al., 2009)). Therefore any discussion of the factors that enabled ferroan magmatism to occur must consider the petrogenesis of each of these three groups of ferroan intraplate associations.

Ferroan granitoids associated with anorthosite and iron-rich mafic rocks are unusually abundant in the Proterozoic (Ashwal, 1993, 2010; Table 2 and Fig. 10). Hoffman (1989) proposed that the near-restriction of massif anorthosites and their associated rapakivi granites to the Proterozoic was related to a supercontinent that was present throughout the middle Proterozoic. The supercontinent acted as a thermal blanket, which reduced heat loss from the underlying mantle and led to a mantle superswell consisting of convective upwelling that was thousands of kilometers in diameter. This resulted in basaltic magmatism that produced anorthosites and associated ferroan granites over a broad area. Hoffman's theory is consistent with the temporal distribution of anorthosites and rapakivi granites, with the large size of Proterozoic rapakivi batholiths, and with the extensive areas of these ferroan granites exposed in areas like southwest U.S. and Finland. Compositionally similar Phanerozoic ferroan granites, including the pan-African granites of the Arabian-Nubian shield (Stoeser and Frost, 2006) and the Triassic to Jurassic younger Nigerian Granites (Jacobson et al., 1958), while also formed in extending continental crust, are smaller and far less voluminous than the Proterozoic examples.

Ferroan alkaline magmatism is rare in the Archean but well-represented in the Proterozoic and Phanerozoic, where it is commonly associated with continental rifts. The most spectacular Proterozoic example is the Gardar province and familiar Phanerozoic provinces include the 117–141 Ma Monteregrian Hills (Eby, 1985) and the East African Rift (King, 1966). Alkaline magmatism results from one of two processes. One process calls for minor amounts of melting of normal mantle, wherein strongly compatible elements such as sodium and ferric iron are preferentially extracted from melting of clinopyroxene. A second process is through melting of a mantle that previously has been enriched by Na-metasomatism. These metasomatizing fluids are usually considered to be produced by dehydration of subducted sea-floor basalts that were enriched in Na_2O during seafloor alteration (Markl et al., 2010).

There are several possibilities for why ferroan alkaline intraplate magmatism is rare in the Archean rock record. First, it is possible that ferroan alkaline rocks were formed but were not preserved, for example, if the alkaline magmas intruded crust that was subsequently subducted (Blichert-Toft et al., 1996). Second, intraplate alkaline magmas may not have formed prior to the Late Archean because conditions were not appropriate. For example, it may have been that cratons were not extensive or thick and rigid enough to allow for the deep rifting necessary to produce continental alkaline ferroan magmatism. Alternatively, the rareness of alkaline rocks

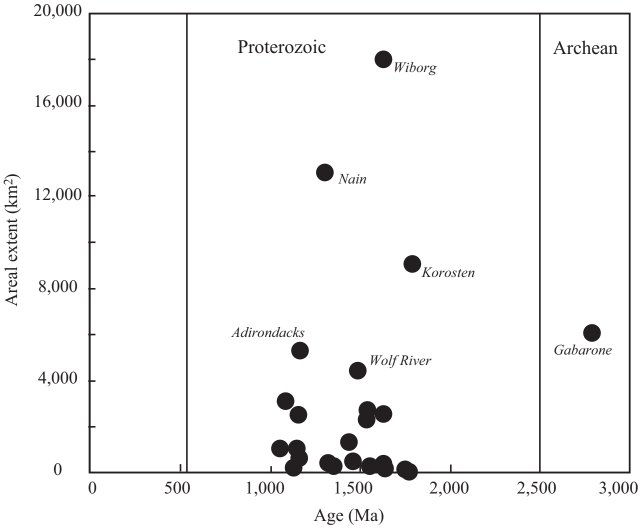

Fig. 10. Age vs. estimated areal extent of ferroan granitoids associated with massif anorthosite. Most occurrences, including those with the largest estimated areal extent, are restricted to the Proterozoic, between 1.0 and 1.8 Ga. The largest bodies are labeled. Data from Table 2. Riga is not plotted because, although the extent of the batholith is estimated at 57,500 km^2, little is exposed and the proportions of rock types are poorly known.

could be a consequence of higher heat flow in the Archean. That the mantle was hotter in the Archean is indicated by the abundance of komatiites in the Archean and their near-absence in the post-Archean record. With such a hot mantle, it is possible that the conditions required to produce low-degree partial melts parental to ferroan alkaline rocks were not attained (Blichert-Toft et al., 1996). Moreover, altered basalt subducted into the Archean mantle would have dehydrated long before it reached the depths necessary for the production of a fluid that would metasomatize overlying mantle. Without a metasomatized mantle, later melting events would not produce large amounts of alkaline magma.

The third group of intraplate ferroan rocks, the calc-alkalic ferroan metaluminous and peraluminous plutons, are not restricted to the Proterozoic, but are found in small volumes in the Archean. Examples include the 3.1–2.8 Ga peraluminous granites of Barberton (Meyer et al., 1994), portions of the 2.85 Ga Bighorn batholith (Frost et al., 2006), and the 2.7 Ga Carajas province (de Mesquita Barros et al., 2009). Plutons of this composition are also found in the Phanerozoic of eastern Australia (Collins et al., 1982; Landenberger and Collins, 1996). The reason that ferroan calc-alkalic rocks are found throughout geologic history is because they are the product of partial melting of tonalitic and granodioritic crust (Frost and Frost, 2011), and crustal melting is a consequence of numerous tectonic processes.

In conclusion, we can identify three distinct types of intraplate ferroan rocks in Proterozoic terrains: metaluminous, alkali-calcic to alkali granites associated with anorthosite and ferroan mafic rocks, strongly ferroan alkaline rocks formed in continental rifts, and calc-alkalic ferroan plutons formed by crustal melting. Of these three associations, the metaluminous granites associated with anorthosite are by far the most voluminous, and the abundance of Proterozoic intraplate ferroan rocks is almost entirely attributable to these granitoids.

Acknowledgments

This paper is an outgrowth of a number of NSF grants to the authors supporting research on the Sherman batholith and Laramie Anorthosite Complex. It is a contribution to IGCP-510, "A-type granites and related rocks through time." The authors thank the reviewers for their helpful comments on the manuscript.

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