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Baddeleyite (ZrO_2) and zircon ($ZrSiO_4$) from anorthositic rocks of the Laramie anorthosite complex, Wyoming: Petrologic consequences and U-Pb ages

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Abstract

The Zr-bearing minerals baddeleyite (ZrO_2) and zircon ($ZrSiO_4$) occur within plagioclase-rich (61–95% plagioclase) cumulates of the Laramie anorthosite complex (LAC), southeastern Wyoming. In each of the examined samples, zircon is present as relatively coarse (1–2 mm) interstitial grains, and baddeleyite occurs as small (0.05 mm) inclusions within cumulus plagioclase. Zircon crystallized between cumulus plagioclase crystals near solidus temperatures from highly fractionated, Zr-saturated liquids. The resultant shape of zircon was controlled by the form of the remaining pore space. The origin of baddeleyite in the anorthositic rocks of the LAC is less well constrained. It may have crystallized early from the anorthositic parental magmas at relatively low silica activities; however, this would require baddeleyite saturation at extremely low Zr concentrations in the parental magmas ($\ll$100 ppm).

Baddeleyite and zircon U-Pb ages reveal that several petrologically distinct intrusions were emplaced and crystallized in the LAC over a relatively restricted 1–3 m.y. interval at ca. 1434 Ma. The $^{207}Pb/^{206}Pb$ ages obtained for the baddeleyite and zircon in each sample are identical within error ($\pm$1–3 m.y.), and U concentrations are uniformly low (<240 ppm), supporting a genetically related origin for the minerals. Two anorthositic layered cumulates and a crosscutting, oxide-rich troctolite from the Poe Mountain anorthosite have crystallization ages that are identical within error: 1434.4 $\pm$ 0.6, 1434.5 $\pm$ 0.6, and 1434.1 $\pm$ 0.7 Ma, respectively. The only earlier period of anorthositic magmatism that can be identified from the Poe Mountain anorthosite is represented by a leucogabbroic xenolith (1436.2 $\pm$ 0.6 Ma), which settled onto the floor of the magma chamber that produced the layered cumulates. A sample composed almost entirely of zoned, iridescent, plagioclase megacrysts from the Chugwater anorthosite yields a baddeleyite age of 1435.4 $\pm$ 0.5 Ma, intermediate between the ages of the xenolith and the layered anorthositic rocks.

All the ca. 1.4–1.5 Ga anorthosites in North America, including the LAC, are located near or on Paleoproterozoic boundaries between Archean cratons and accreted Proterozoic island arc terranes. These preexisting crustal structures appear to play a major role in the origin and ascent of anorthositic magmas. The evidence for anorthositic magmatism at 1.43 Ga in the LAC suggests that there may be a strong genetic link between these high-temperature mafic magmas and the regional production of anorogenic granites in the western and southwestern U.S., many of which have similar crystallization ages in the interval of 1.43–1.44 Ga.

Introduction

Recent studies have shown that zircon and baddeleyite can be recovered from some anorthositic rocks in Proterozoic anorthosite complexes, and that precise U-Pb ages can be determined from both minerals (McLelland and Chiarenzelli, 1990; Doig, 1991; Higgins and van Breemen, 1992; van Breemen and Higgins, 1993; Martignole et al., 1993; Paces and Miller, 1993; Duchesne et al., 1993; Owens et al., 1994; Amelin et al., 1994). Baddeleyite, in particular, has proven to be a useful mineral for U-Pb dating in mafic rocks because it has negligible initial common Pb, experiences little or no Pb loss, and rarely occurs as xenocrysts (Heaman and LeCheminant, 1993). In conjunction with field relationships, this ability for precise dating potentially allows for detailed documentation of the intrusive history of the mafic portions of individual complexes, some of which contain as many as 20 separate anorthositic intrusions [e.g., Harp Lake (Emslie, 1980); Nain (Yu and Morse, 1993)]. This may be particularly useful where emplacement-related recrys-

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tallization has obscured primary contacts between intrusions. Because the relative stability of baddeleyite and zircon is related to silica activity (Butterman and Foster, 1967), the textural and morphological relationships between these two minerals and the rocks they crystallized within may also help to constrain the crystallization path of anorthosite.

The Laramie anorthosite complex (LAC), southeastern Wyoming, contains the only major exposure of middle Proterozoic anorthositic rocks in the western and southwestern U.S. (Frost et al., 1993). The Nain and Grenville provinces of Canada contain numerous anorthositic intrusions of middle Proterozoic age (Ashwal, 1993), however, intrusive rocks of the exposed Proterozoic crust in the western U.S. are dominated by relatively high-level granitic batholiths with crystallization ages between 1.49 and 1.40 Ga (Anderson, 1983). It has been proposed that mafic magmatism at depth was the driving force for the large-scale crustal melting necessary to produce the granites (Anderson and Bender, 1989), but direct ages of crystallization for coeval mafic rocks in this region are notably lacking. The age of the anorthositic rocks in the LAC is known only indirectly through the age of a crosscutting monzonite (Frost et al., 1990). Thus, the purposes of this study are (1) to determine directly the ages of crystallization of a variety of anorthositic rocks from the LAC to limit the duration of middle Proterozoic mafic magmatism in southeastern Wyoming; (2) to investigate the geochronological relationships among the LAC, other middle Proterozoic anorthosites, and similarly aged granitic batholiths in North America; and (3) to investigate the morphologic and textural characteristics of baddeleyite and zircon as guides to the crystallization history of anorthositic rocks.

Geology of the Laramie anorthosite complex

The unmetamorphosed and undeformed 725 km^2 LAC outcrops in the southern Laramie Mountains, southeastern Wyoming (Fig. 1). Only a portion of the LAC is presently exposed; west-dipping Laramide (Late Cretaceous to early Tertiary) thrust and high-angle reverse faults truncate the eastern margins, and shallowly dipping, early Paleozoic sediments unconformably overlie the western margins. The LAC intruded Archean gneisses of the Wyoming province in the north and Proterozoic supracrustal rocks in the south (Fig. 1). It probably intruded along the Cheyenne belt (Frost et al., 1993), the ca. 1.78 Ga collisional zone that separates the Archean rocks from the accreted Proterozoic island arc terranes in the south (Karlstrom and Houston, 1984).

The LAC consists of a central mass of anorthositic rocks (550 km^2) that was intruded by dioritic and troctolitic rocks of the Strong Creek complex (Mitchell, 1993), monzonitic rocks of the Maloin Ranch pluton (Kolker and Lindsley, 1989; Kolker et al., 1990, 1991), the Sybille intrusion (Fuhrman et al., 1988), and the Red Mountain pluton (Anderson et al., 1987, 1988), and granitic rocks of the Sherman batholith (Geist et al., 1989) (Fig. 1). Estimates of emplacement pressures for the monzonitic rocks (equilibria among pyroxenes, olivine, and quartz) yield midcrustal pressures of about 3 kbar in the north and 4 kbar in the south (Fuhrman et al., 1988; Kolker and Lindsley, 1989). Three major composite anorthositic intrusions are contained within the LAC: the Poe Mountain, Chugwater, and Snow Creek anorthosites (Figs. 1 and 2).

The Poe Mountain anorthosite consists of (1) a central core of pervasively recrystallized megacrystic anorthosite, (2) a marginal layered series containing a 5–7 km thick package of layered and laminated anorthositic and leucogabbroic cumulates, (3) a suite of igneous xenoliths, ranging in composition from leucogabbro to anorthosite, and (4) a series of late, undeformed troctolitic intrusions (Fig. 2) (Scoates, 1994). The central core area of the Poe Mountain anorthosite contains mainly homogenous, recrystallized anorthosite of uniform plagioclase composition ($\sim An_{46}$) with little evidence of primary igneous structures or textures. Where zones of relatively weak recrystallization occur, the protolith appears to be composed of coarse-grained (2–4 cm) megacrysts of plagioclase. The surrounding marginal layered series contains two distinct layered zones: an inner anorthositic layered zone (ALZ) and an outer leucogabbroic layered zone (LLZ). The overall shape of the intrusion is domical. Layering is steepest along the outer margins of the Poe Mountain anorthosite, dipping 60–90°, and layering shallows considerably toward the central core, dipping 30–60°. The contact between the two layered zones is continuous along strike, across several Laramide faults, for ~20 km. Each layered zone is, in turn, subdivided into distinct layered sections (lower, middle, and upper) on the basis of layering characteristics and cryptic geochemical variations (Scoates, 1994) (Fig. 2). The base of the lowermost ALZ cannot be identified in the field because the effects of high-temperature recrystallization that were produced during late emplacement deformation (Lafrance et al., 1994) are pervasive in the interior of the Poe Mountain anorthosite. The uppermost portions of the upper LLZ are missing because of subsequent emplacement of the Sybille intrusion (Fig. 2). Well-developed igneous layering and a prominent plagioclase lamination are characteristic of anorthositic cumulates throughout the entire layered series. Rocks in the layered series are composed of cumulus plagioclase (An_{45-55}), oikocrystic clinopyroxene, inverted pigeonite, olivine, ilmenite, and magnetite, with interstitial apatite and sulfides and late biotite.

A suite of igneous xenoliths, ranging in composition from anorthosite to leucogabbro, is found throughout the layered series. These xenoliths are mineralogically similar to the layered series and consistently have more calcic plagioclase compositions and lower initial Sr isotopic ratios than their host cumulates (Scoates and Frost, 1994; Scoates, 1994). They therefore appear to represent a separate and distinct product of anorthositic magmatism in the LAC. Small troctolitic (plagioclase + olivine) intru-

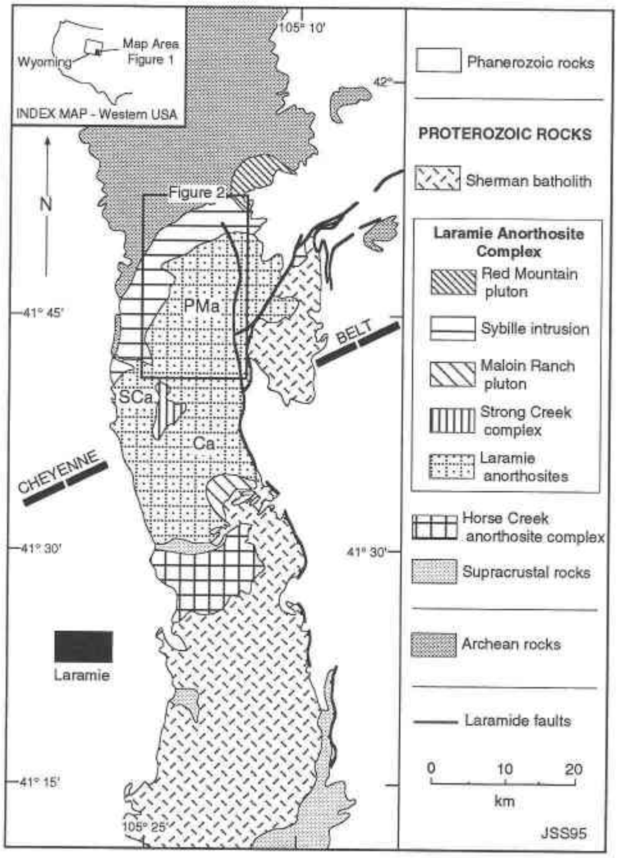

Fig. 1. Geologic map of the southern Laramie Mountains of southeastern Wyoming, showing the location of the Laramie anorthosite complex and the inferred trace of the Cheyenne belt through the Laramie Mountains. PMa = Poe Mountain anorthosite, Ca = Chugwater anorthosite, and SCa = Snow Creek anorthosite.

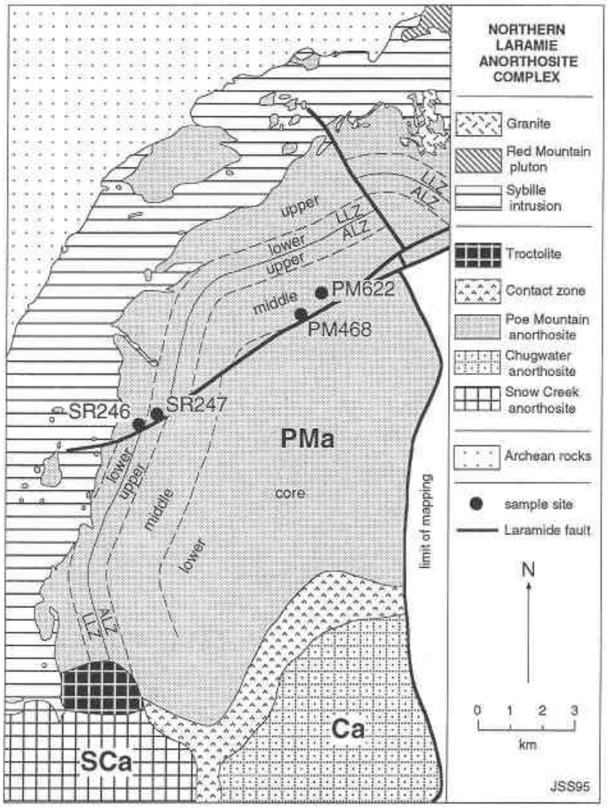

Fig. 2. Simplified geologic map of the northern Laramie anorthosite complex. The four geochronological sample sites from the Poe Mountain anorthosite are shown as solid circles. ALZ = anorthositic layered zone, and LLZ = leucogabbroic layered zone. The contact between the ALZ and LLZ is shown as a solid line, and the contacts between layered sections within the two layered zones (lower, middle, and upper in the ALZ, and lower and upper in the LLZ) are shown as dashed lines. The "contact zone" denotes the area where pervasive emplacement-related recrystallization overprinted the primary magmatic contacts between the Poe Mountain, Chugwater, and Snow Creek anorthosites.

sions occur throughout the Poe Mountain anorthosite. The largest truncates the southwestern extension of the layered series (Fig. 2). Coarse-grained troctolite is also found associated with massive ilmenite in the Sybille iron titanium oxide deposit (Bolsover, 1986; Epler, 1987), where angular inclusions of anorthosite indicate that anorthosite was completely solidified prior to intrusion of troctolite.

The Chugwater anorthosite (Fig. 2) consists of interfingered lenses of recrystallized anorthosite and undeformed megacrystic anorthosite and troctolite (Frost et al., 1993). There are no laterally continuous, layered cumulates in the Chugwater anorthosite, and well-zoned, iridescent plagioclase megacrysts are common. Plagioclase compositions are uniformly more calcic in the Chugwater anorthosite ($>An_{50}$) than in the core of the Poe Mountain anorthosite ($\sim An_{46}$). The smaller Snow Creek anorthosite occurs in the west-central LAC (Fig. 2) and consists of recrystallized megacrystic anorthosite with abundant zoned, iridescent plagioclase megacrysts (Mitchell, 1993). Contact relationships between the Poe Mountain anorthosite to the north and the Chugwater and Snow Creek anorthosites are not easily identifiable in the field because all primary igneous structures in the area have been overprinted by the effects of high-temperature emplacement-related deformation. The approximate locations of intrusion contacts in this area are marked by a gradational contact zone in Figure 2.

Intrusive relationships indicate that anorthosite is the oldest lithology in the LAC (Frost et al., 1993). In the northern LAC, the Poe Mountain anorthosite was intruded by monzonitic rocks of the Sybille intrusion that, in turn, were intruded by the Red Mountain pluton (Figs. 1 and 2). Frost et al. (1990) determined the uranium-lead zircon age for a fayalite monzonite in the Red Mountain pluton to be 1439 $^{+7}_{-6}$ Ma, subsequently revised to 1431.3 ± 1.3 Ma (C. D. Frost, personal communication). In accordance with field relationships, this is a minimum age for intrusive activity in the northern part of the LAC and a minimum age for the anorthositic rocks. The only previous study that attempted to determine directly the age of anorthositic rocks in the LAC used Rb-Sr isotopic systematics (Subbarayudu, 1975). No meaningful isochrons were derived, however, because of the complex, open-system crystallization history of the anorthositic rocks with respect to Sr isotopes, which is the result of crustal contamination and magma mixing (Scoates and Frost, 1994).

Sampling strategy and analytical techniques

Anorthositic rocks are predominantly plagioclase-rich adcumulates. Textural evidence suggests that they typically include only minor amounts of trapped interstitial liquid that could be enriched in incompatible elements. Thus, whole-rock samples contain only minor amounts of U-rich trace minerals suitable for U-Pb geochronology. In the Poe Mountain anorthosite, this is reflected by low Zr contents in both the ALZ (16–73 ppm) and the LLZ (12–106 ppm) (Scoates, 1994). We processed >100 kg of each sample in this study to extract sufficient quantities of U-rich minerals for analysis. Each of the five samples reported in this study, ranging in plagioclase abundance from 61–95%, contained both baddeleyite and zircon.

Heavy minerals were concentrated from crushed samples by standard density and magnetic separation procedures. No cores in baddeleyite or zircon were visible with the binocular microscope under high-power magnification (50×). Small inclusions were visible in some of the concentrated baddeleyite and zircon, but grains selected for analysis were optically devoid of inclusions. The grains were cleaned in cold 2*N* HNO_3 prior to dissolution. Both baddeleyite and zircon were dissolved in concentrated HF and HNO_3 in teflon microvessels following the procedure of Parrish (1987) and converted to chlorides. Aliquots of sample solutions were spiked with a mixed $^{235}U/^{208}Pb$ spike. Pb and U were purified in anion-exchange columns using HCl chemistry modified from Krogh (1973). The total Pb blank decreased significantly during the course of this study, from 80 to 5 pg. The blank composition was $^{206}Pb/^{204}Pb$ = 19.09, $^{207}Pb/^{204}Pb$ = 15.652, and $^{208}Pb/^{204}Pb$ = 38.31 and was used in corrections for blank contributions. The Pb and U samples were loaded onto single rhenium filaments for isotopic analysis by thermal emission mass spectrometry. The H_3PO_4-silica gel technique was used for Pb, and U was loaded with H_3PO_4 and graphite and run as metal ions. The isotopic analyses were conducted at the University of Wyoming on a multiple-collector, VG Sector mass spectrometer. Mass discrimination factors for Pb and U were determined by multiple analyses of NBS SRM 981 and U-500, respectively, and were 0.094 ± 0.056% per atomic mass unit for Pb and 0 ± 0.06% per atomic mass unit for U. The program PBDAT (Ludwig, 1988a) was used to reduce the raw mass spectrometer data, correct for blanks, and calculate uncertainties. Much of the data from the analyzed fractions overlaps concordia, and the $^{207}Pb/^{206}Pb$ ages of analyzed fractions from each sample are nearly identical. Therefore, the weighted average $^{207}Pb/^{206}Pb$ ages (weighted by the inverse variance of the individual ages) were calculated rather than linear regressions. The weighted average ages and uncertainties were calculated using ISOPLOT (Ludwig, 1988b), and errors are quoted at 2σ.

Zircon and baddeleyite morphologies

In four of the five samples examined, zircon is far more abundant than baddeleyite (on the order of thousands to one), although the total abundance of zircon is typically <0.2% of the whole rock. All analyzed zircon crystals were colorless, anhedral fragments. Texturally, zircon occurs as a late-crysallizing phase interstitial to cumulus plagioclase (Fig. 3A). Contacts between zircon and other minerals are sharp and devoid of secondary alteration products, indicating that the original morphology of zircon was not modified subsequent to crystallization. In thin section, zircon is typically 1 mm in diameter, with the largest grains up to 1.5 mm across. The analyzed grains were much smaller (0.25–0.50 mm) and were probably fragments of larger grains. Poikilitic zircon is common (Fig. 3B) and is further textural evidence for late interstitial crystallization. Euhedral zircon was not found in any of the mineral separates. Many of the grains selected for analysis were characterized by minute ripple-like structures across their outer surfaces, observable under both moderate- to high-power magnification (20–50×) with a binocular microscope and a scanning electron microscope (SEM). These structures may be a manifestation of nonplanar (skeletal) growth, perhaps reflecting rapid growth from a late-stage zircon supersaturated melt (Bossart et al., 1986).

Baddeleyite is present in all samples and exhibits morphological and textural characteristics markedly different from those of zircon. It occurs as small euhedral to subhedral grains within cumulus plagioclase (Fig. 3C and 3D) and is not observed interstitially with zircon. The occurrence of baddeleyite is not related to fractures or healed fractures in plagioclase, indicating that it did not form by secondary alteration processes. No rims of zircon were observed, optically or with the SEM, on baddeleyite. Average grain size is about 0.05 mm, and the largest observed grains are 0.2–0.3 mm in diameter. Baddeleyite is commonly concentrated in select plagioclase grains within a given thin section. It is restricted to the cores of plagioclase grains and does not occur in the relatively potassic marginal areas that contain alkali feldspar exsolution lamellae. Where multiple grains are observed in a single plagioclase grain, there is typically no preferred orientation, although examples of parallel orientation were observed. Analyzed baddeleyite grains were translucent brown, and many grains displayed the well-developed polysynthetic twinning that is characteristic of baddeleyite (Smith and Newkirk, 1965; Heaman and LeCheminant, 1993).

U-Pb RESULTS

The U-Pb isotopic compositions of 15 baddeleyite and four zircon fractions (Table 1) were determined from five samples: four from the Poe Mountain anorthosite (Fig. 2), including one from each of the two layered zones (ALZ and LLZ), a crosscutting troctolite, and a leucogabbroic xenolith, and one sample from the Chugwater anorthosite. Between 40 and 120 grains of baddeleyite and zircon were dissolved for each analysis. The concentrations of U and Pb are extremely low, ranging from 43 to 238 ppm U and 10 to 55 ppm Pb for baddeleyite, and 9 to 127 ppm U and 3 to 34 ppm Pb for zircon. These concentrations are typical of Proterozoic anorthosites (e.g., Higgins and van Breemen, 1992; Martignole et al., 1993; van Breemen and Higgins, 1993; Owens et al., 1994) and are consistent with the crystallization of baddeleyite and zircon from U-poor parental magmas. Even with these low concentrations, $^{206}Pb/^{204}Pb$ values (corrected for fractionation, spike composition, and blank contribution) are extremely high, ranging from 3680 to 285 360 (Table 1), thus indicating very low contributions of initial Pb.

The U-Pb data cluster near concordia (0–1.1% discordance), demonstrating the closed-system behavior of baddeleyite and zircon with respect to Pb loss or U gain. There is no discernible difference within error between baddeleyite and zircon $^{207}Pb/^{206}Pb$ ages within each sample. Because of this, we consider the weighted average $^{207}Pb/^{206}Pb$ ages of combined baddeleyite and zircon to be the best estimate of crystallization age.

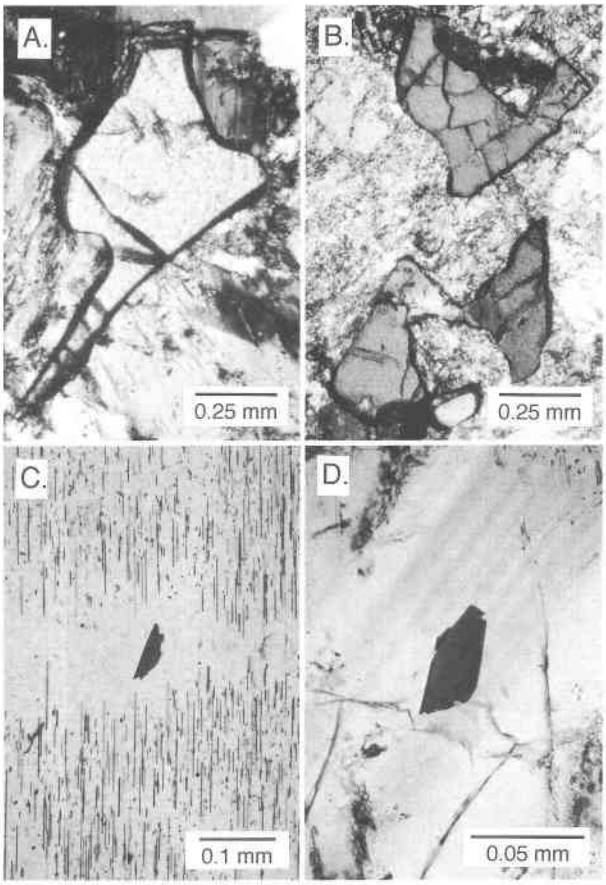

Fig. 3. Representative photomicrographs of zircon and baddeleyite morphologies in anorthositic rocks of the Poe Mountain anorthosite. (**A**) Interstitial zircon, (**B**) poikilitic zircon, (**C** and **D**) baddeleyite inclusions in plagioclase.

Oikocrystic anorthosite (PM468)—ALZ, Poe Mountain anorthosite (latitude 41°46′03″, longitude 105°21′58″)

Sample PM468 is from a well-laminated anorthosite (93% plagioclase) containing abundant, regularly spaced clinopyroxene, olivine, and iron titanium oxide oikocrysts. Stratigraphic reconstructions place it 2240 m below the ALZ/LLZ contact. The data from three baddeleyite fractions and one zircon fraction are nearly concordant (0.6–0.9% discordance), with $^{207}Pb/^{206}Pb$ ages of 1433.9–1434.8 Ma for baddeleyite and 1434.8 Ma for zircon (Fig. 4A). The weighted average $^{207}Pb/^{206}Pb$ age of 1434.4 ± 0.6 Ma is considered the best estimate for the crystallization age of PM468.

Laminated leucogabbro (SR247)—LLZ, Poe Mountain anorthosite (latitude 41°44′27″, longitude 105°22′19″)

Sample SR247 is from a well-laminated leucogabbro occurring 3240 m stratigraphically above PM468. The U-Pb data for three baddeleyite fractions are nearly concordant (0.3–0.8% discordance), and the zircon fraction is concordant (Fig. 4B). They yield a weighted average $^{207}Pb/^{206}Pb$ age of 1434.5 ± 0.6 Ma. Thus, the crystallization ages of anorthositic cumulates from both the ALZ and LLZ agree within uncertainty.

Troctolite (PM622)—Poe Mountain anorthosite (latitude 41°46′45″, longitude 105°21′06″)

Sample PM622 is from a coarse-grained, oxide-apatite-rich troctolite (61% plagioclase) associated with massive iron titanium oxide ore in the Sybille deposit (Bolsover, 1986; Epler, 1987; Lindsley and Frost, 1990). The weighted average $^{207}Pb/^{206}Pb$ age of four nearly concordant fractions (three baddeleyite and one zircon; 0.6–0.9% discordance) is 1434.1 ± 0.7 Ma (Fig. 4C). Localized shearing of the enveloping anorthositic cumulates and inclusions of anorthosite xenoliths in the undeformed troctolite indicate that the anorthosite was consolidated prior to intrusion of the troctolite. There are, however, no resolvable differences between the ages of the layered series cumulates and this crosscutting troctolite.

Leucogabbroic xenolith (SR246)—Poe Mountain anorthosite (latitude 41°44′16″, longitude 105°25′45″)

Sample SR246 is from a leucogabbroic xenolith (83% plagioclase), with a minimum length of 50 m and an internal fabric defined by plagioclase lamination that is

TABLE 1. U-Pb results for baddeleyite and zircon fractions separated from anorthositic rocks of the LAC

Description*		Concentration			Measured atomic ratios**				Ages (Ma)				
Fraction	Weight (mg)	U (ppm)	Pb (ppm)	Common Pb (pg)†	$^{206}Pb/^{204}Pb$‡	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$§	Rho	D‖
PM468: Poe Mountain anorthosite, ALZ													
B (nm1)	0.397	49	12	101	13138	0.2481(0.45)	3.093(0.46)	0.090406(0.09)	1429.0	1431.1	1434.1(1.7)	0.98	0.60
B (d-1)	0.139	64	15	42	32776	0.2476(0.29)	3.088(0.31)	0.090437(0.10)	1426.2	1429.7	1434.8(1.9)	0.94	0.85
B (m2)	0.149	90	21	23	35447	0.2475(0.27)	3.085(0.28)	0.090396(0.07)	1425.6	1428.9	1433.9(1.4)	0.97	0.83
Z (d-2)	0.464	110	31	78	31535	0.2479(0.40)	3.091(0.41)	0.090437(0.07)	1427.4	1430.4	1434.8(1.3)	0.99	0.75
SR247: Poe Mountain anorthosite, LLZ													
B (nm1)	0.447	71	17	135	8164	0.2488(0.40)	3.101(0.41)	0.090405(0.07)	1432.2	1433.0	1434.1(1.4)	0.98	0.34
B (m1)	0.437	60	14	188	3680	0.2476(0.37)	3.087(0.40)	0.090423(0.14)	1426.3	1429.6	1434.5(2.7)	0.94	0.84
B (m3)	0.201	68	16	24	29668	0.2481(0.25)	3.094(0.26)	0.090441(0.06)	1428.7	1431.2	1434.9(1.2)	0.97	0.67
Z (nm1)	0.724	9	3	44	13819	0.2492(0.46)	3.105(0.50)	0.090382(0.18)	1434.3	1434.0	1433.6(3.5)	0.93	—
PM622: Poe Mountain anorthosite, oxide-rich troctolite													
B (m1)	0.422	192	46	324	4794	0.2481(0.48)	3.092(0.49)	0.090407(0.10)	1428.5	1430.8	1434.1(1.9)	0.98	0.63
B (m2)	0.348	86	20	30	79812	0.2476(0.45)	3.086(0.53)	0.090375(0.29)	1426.3	1429.2	1433.5(5.6)	0.84	0.74
B (m3)	0.268	182	43	29	165750	0.2475(0.24)	3.086(0.25)	0.090415(0.06)	1425.7	1429.2	1434.3(1.1)	0.97	0.85
Z (d-2)	0.408	90	26	51	41176	0.2474(0.40)	3.082(0.44)	0.090359(0.16)	1424.8	1428.2	1433.1(3.1)	0.93	0.82
SR246: Poe Mountain anorthosite, LLZ xenolith													
B (d-1)	0.546	76	18	41	228640	0.2492(0.32)	3.110(0.33)	0.090513(0.06)	1434.2	1435.1	1436.4(1.2)	0.98	0.35
B (d-3)	0.179	43	10	31	25158	0.2499(0.30)	3.118(0.31)	0.090478(0.09)	1438.0	1437.0	1435.6(1.7)	0.96	—
Z (d-2)	0.668	127	34	232	8649	0.2484(0.40)	3.100(0.40)	0.090508(0.07)	1430.4	1432.8	1436.3(1.4)	0.98	0.66
BM136: Chugwater anorthosite, iridescent megacrystic anorthosite													
B (nm1)	0.521	109	26	415	2516	0.2480(0.42)	3.092(0.46)	0.090447(0.18)	1428.0	1430.0	1435.0(3.4)	0.92	0.74
B (m1)	0.447	238	55	45	285360	0.2471(0.36)	3.082(0.37)	0.090450(0.06)	1423.5	1428.1	1435.0(1.2)	0.99	1.07
B (d-1)	0.258	81	19	50	28224	0.2472(0.25)	3.084(0.26)	0.090476(0.07)	1424.3	1428.8	1435.6(1.3)	0.96	1.08
B (m2)	0.298	120	28	20	156380	0.2476(0.35)	3.088(0.35)	0.090478(0.06)	1425.9	1429.8	1435.6(1.2)	0.98	0.95

* Minerals analyzed: B = baddeleyite, Z = zircon. Magnetic properties and side angle of Franz magnetic splitter in parentheses.
** Atomic ratios corrected for fractionation, spike composition, blank contribution, and common Pb (Stacey and Kramers, 1975); 2σ percent errors in parentheses.
† Total common Pb, including sample, spike, and blank.
‡ The $^{206}Pb/^{204}Pb$ corrected for fractionation, spike composition, and blank contributions.
§ Errors of the $^{207}Pb/^{206}Pb$ ages are quoted at 2σ in parentheses.
‖ D = discordance in percent.

oblique to the fabric in the enveloping LLZ leucogabbros. It also contains several iridescent plagioclase megacrysts, which are not found in the layered cumulates of either the ALZ or LLZ. The weighted average $^{207}Pb/^{206}Pb$ age of three analyzed fractions (two baddeleyite and one zircon) is 1436.2 + 0.6 Ma (Fig. 4D). The leucogabbroic xenolith is resolvably older than the LLZ cumulates that contain it, and thus the occurrence of a distinct earlier phase of anorthositic magmatism in the LAC has been identified.

Megacrystic anorthosite (BM136)—Chugwater anorthosite (latitude 41°34′20″, longitude 105°23′52″)

Sample BM136 is from a megacrystic anorthosite (95% plagioclase) from the Chugwater anorthosite. It occurs in a relatively unrecrystallized lens, 100 m wide, within pervasively recrystallized anorthosite and may represent either a late intrusive phase of the Chugwater anorthosite or a low-strain window in the recrystallized anorthosites. It is compositionally distinct from the Poe Mountain anorthosites to the north and is composed of abundant iridescent plagioclase megacrysts, up to 4 cm in diameter, showing strong oscillatory zoning, normal and reverse zoning, and prominent resorption surfaces. In contrast to the other four samples in this study, baddeleyite is far more abundant than zircon in BM136. The weighted average $^{207}Pb/^{206}Pb$ age of four baddeleyite fractions is 1435.4 ± 0.5 Ma (Fig. 4E). This age overlaps within error the younger ages of the Poe Mountain layered series samples and the older age of the xenolith; the megacrystic anorthosite may be the same age as the layered series cumulates to the north or as much as 2 m.y. older.

ORIGIN OF ZIRCON AND BADDELEYITE IN THE LARAMIE ANORTHOSITES

In mafic rocks, baddeleyite and zircon are most commonly found in late interstitial regions or coarse pegmatoids (e.g., Heaman and LeCheminant, 1993). The results of this study, however, indicate a separate crystallization history for baddeleyite and zircon in anorthositic rocks of the LAC. The co-occurrence of baddeleyite and zircon in anorthositic samples has rarely been reported. Amelin et al. (1994) provided U-Pb data for both baddeleyite and zircon from a gabbro-anorthosite (sample 7/90) in the Korosten complex, Ukraine, and showed that the $^{207}Pb/^{206}Pb$ ages of fractions of both minerals are identical within error. Although the physical settings of these minerals in the sample are not noted, their morphological descriptions are strikingly similar to those described in this study.

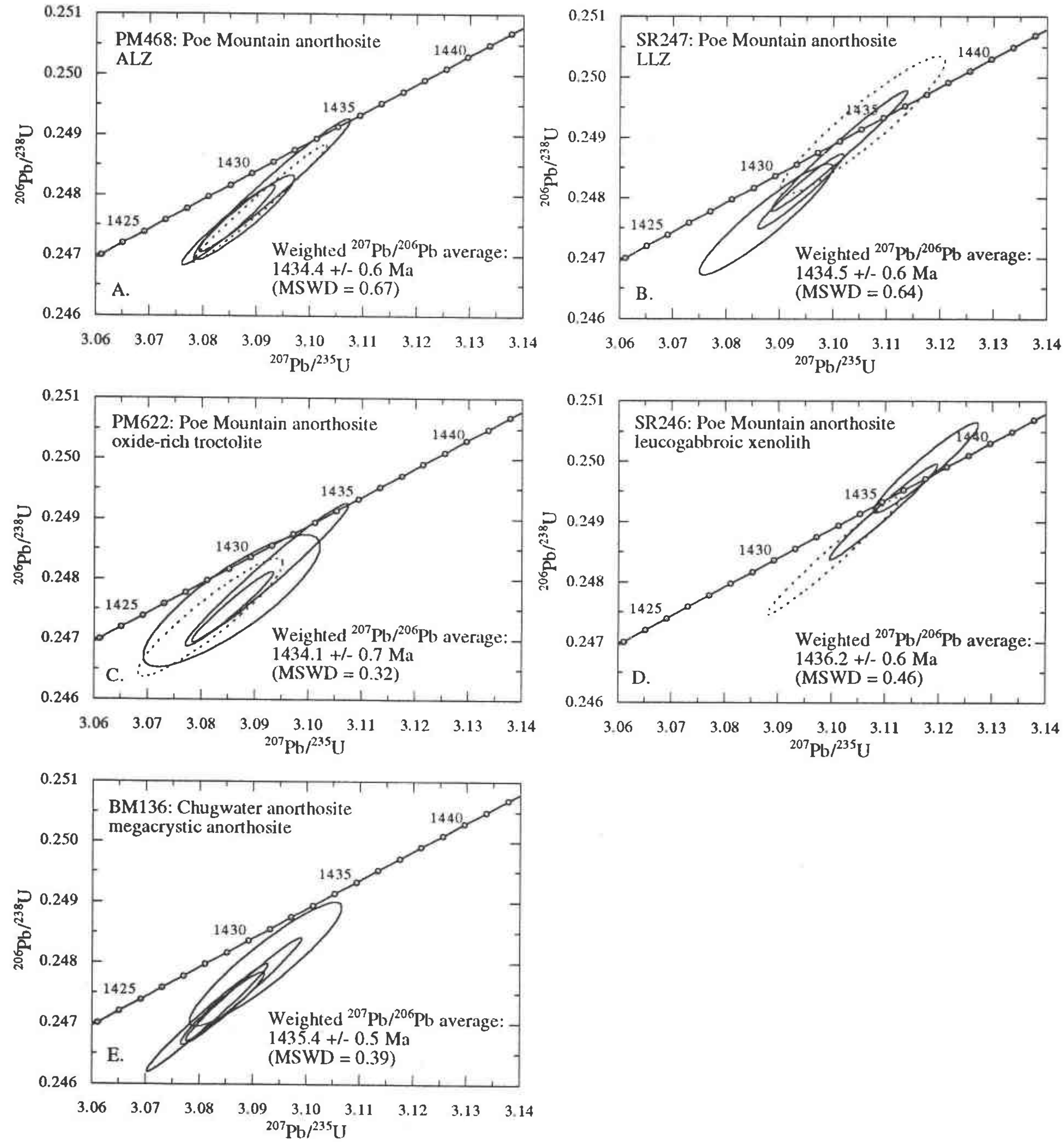

Fig. 4. Concordia plots for U-Pb data from analyzed baddeleyite and zircon fractions. Each ellipse represents the result of the analysis of a single fraction. Solid line ellipses = baddeleyite, and dashed line ellipses = zircon. **(A)** PM468: anorthosite, ALZ, Poe Mountain anorthosite; **(B)** SR247: leucogabbro, LLZ, Poe Mountain anorthosite; **(C)** PM622: coarse-grained oxide-rich troctolite, ALZ, Poe Mountain anorthosite; **(D)** SR246: leucogabbroic xenolith, LLZ, Poe Mountain anorthosite; **(E)** BM136: megacrystic anorthosite, Chugwater anorthosite.

The textural interpretation of zircon in the LAC anorthosites is relatively straightforward. The obvious interstitial and poikilitic habit of zircon indicates that zircon crystallized near or at solidus temperatures in the last available pore spaces of a nearly consolidated plagioclase-rich cumulate. The resultant shape of zircon was strongly influenced by the shape of preexisting plagioclase grains and the shape of the remaining pore space. The optical lack of cores and resorption surfaces, the extremely low U and Pb concentrations, and the extremely high $^{206}Pb/^{204}Pb$ values in zircon indicate that it is unlikely to be inherited. Similar anhedral zircons from anorthosite were

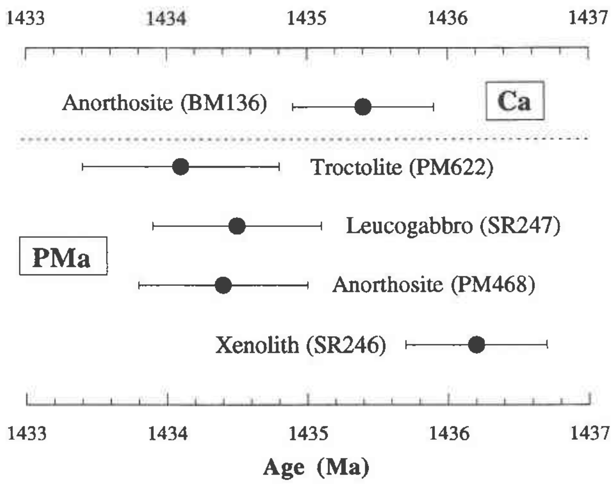

Fig. 5. Comparison of U-Pb ages determined in this study for anorthositic, leucogabbroic, and troctolitic rocks of the Laramie anorthosite complex.

also reported by Martignole et al. (1993) from the Rivière-Pentecôte anorthosite in the east-central Grenville province, Canada. These observations have important implications for U-Pb geochronology because there is little morphological and compositional difference between the zircons analyzed in our study and the demonstrably metamorphic zircons from the Adirondack anorthosites (Chiarenzelli and McLelland, 1993). Thus, it is evident that care is required when interpreting the significance of U-Pb data from anhedral zircon, and textural constraints in thin section should always be considered.

Although the nearly identical U and Pb concentrations and $^{207}Pb/^{206}Pb$ ages of zircon and baddeleyite are strong evidence that baddeleyite is igneous in origin and related to the crystallization history of the anorthositic rocks in the LAC, the mechanism of formation of baddeleyite remains unclear. The two most commonly proposed origins for baddeleyite in mafic rocks are late crystallization from highly fractionated interstitial liquids (Heaman and LeCheminant, 1993) and exsolution from ilmenite (Naslund, 1987; McLelland and Chiarenzelli, 1990; Loferski and Arculus, 1993). Neither mechanism is appropriate for the origin of baddeleyite in the Laramie anorthosites because this baddeleyite occurs in early-crystallized plagioclase and is not associated spatially with discrete grains of ilmenite.

On the basis of the observed textural relations only, baddeleyite in the LAC may have crystallized prior to plagioclase. This would imply lower silica activities in the early crystallization of the anorthosites, prior to late saturation of zircon at elevated silica activities. It would also imply early saturation of baddeleyite in the anorthositic parental magmas at exceedingly low Zr concentrations. If Al-rich gabbroic dikes in the LAC can be considered as representative of parental magmas, this implies Zr concentrations in the 10–60 ppm range (Mitchell et al., 1995). Recent experimental work may help to resolve the origin of baddeleyite in anorthositic rocks of the LAC. Rawling et al. (1995) reported that baddeleyite and intermediate-composition plagioclase are not compatible at 1100 °C, at both 1 atm and 5 kbar, and therefore a true inclusion origin seems to be precluded. No matter what the exact mechanism of origin of baddeleyite, the similarity between the $^{207}Pb/^{206}Pb$ ages of baddeleyite and zircon indicates that the interval of time between the crystallization of the two minerals was within the determined analytical error.

Emplacement and crystallization history of the Laramie anorthosites

The baddeleyite and zircon U-Pb ages that we report span a relatively restricted interval of geologic time in the middle Proterozoic: a maximum interval of 3.4 m.y. and a minimum interval of 0.8 m.y. (Fig. 5). Crystallization ages of both the layered cumulate samples of the Poe Mountain anorthosite and the crosscutting troctolite are indistinguishable within error (<1 m.y.). The two layered cumulate samples are separated by over 3000 m of plagioclase-rich cumulates. If 1 m.y. was the maximum time for the crystallization of ~3000 m of adcumulate rocks, and crystallization was continuous, then a minimum average rate of accumulation of ~0.3 cm/yr is implied. Our estimate is comparable to that of Morse (1979a, 1986) for the crystallization of the plagioclase-rich Kiglapait intrusion (average modal feldspar = 73%; Morse, 1979b) in the Nain plutonic suite, Labrador. He estimated that the crystallization time for the 8400 m thick Layered Group in the Kiglapait intrusion was about 10^6 yr, with an average accumulation rate of about 1 cm/yr.

The leucogabbroic xenolith in the LLZ, with a crystallization age of 1436.2 ± 0.6 Ma, is the only sample from the Poe Mountain suite with a resolvably different age (Fig. 5). However, even the age difference between the xenolith and the rest of the Poe Mountain anorthosite is limited to a minimum of 0.5 m.y. and a maximum of 2 m.y. Numerous other compositionally and isotopically similar igneous xenoliths occur within the ALZ and LLZ of the Poe Mountain anorthosite (Scoates and Frost, 1994; Scoates, 1994), and it is possible that some of these may belong to this earlier 1436 Ma phase of anorthositic magmatism. The xenoliths may have been derived from a preexisting intrusion near or at the level of emplacement of the LAC (~3–4 kbar), or they may have been entrained in ascending magma and derived from depth somewhere along the magma conduit.

Field relationships indicate that the anorthositic rocks are the oldest lithology in the LAC (Frost et al., 1993). Each of the samples in this study has crystallization ages older, outside of error, than the only existing, precise U-Pb age from the LAC, 1431.3 ± 1.4 Ma from the Red Mountain pluton (C. D. Frost, personal communication). Because the Red Mountain pluton is the youngest of the monzonitic intrusions in the northern LAC, it appears that the majority of the intrusions in the LAC, displaying a wide range of compositions, crystallized over a 3–7 m.y. interval.

Regional setting of the 1.43 Ga Laramie anorthosite complex

The LAC is one of over 50 intrusions with crystallization ages between 1.49 and 1.40 Ga contained in a major 4800 km long belt that extends from Labrador to California (Emslie, 1978; Anderson, 1983; Anderson and Morrison, 1992; Gower and Tucker, 1994). The vast majority of these intrusions are granitic batholiths of A-type affinity, commonly referred to as anorogenic granites (Anderson, 1983). However, five intrusions containing anorthosite are known: the 1.43 Ga LAC; the 1.49 Ga Wolf River batholith of Wisconsin (Van Schmus et al., 1975); and three intrusions in Labrador, the 1.45 Ga Harp Lake complex (Krogh and Davis, 1973), the 1.46 Ga Michikamau intrusion (Krogh and Davis, 1973), and the 1.42 Ga Mistastin intrusion (Emslie and Stirling, 1993). As has been observed in the LAC, each of these anorthositic intrusions is near or along collisional zones between Archean cratons and Paleoproterozoic orogens (Gower and Tucker, 1994). This suggests that the presence of preexisting crustal structures (lithospheric weaknesses) facilitates the generation and the ascent of anorthositic magmas. Reactivation of these terrane boundaries may have occurred in response to either regional compression or extension. Nyman et al. (1994) argued on the basis of kinematic data from 1.4 Ga plutons in the southwestern U.S. (Colorado, Arizona, and New Mexico) that a major orogenic event involving contractional or transpressional tectonism and magmatism occurred between 1.4 and 1.5 Ga. Conversely, Gower and Tucker (1994) argued that, although orogenesis may have continued up to 1.45 Ga, a major rifting event extending from Wyoming to Baltica occurred at 1.43 Ga and detached large sections of crust from the southwestern Grenville province. We suggest that an extensional or transtensional environment at 1.43 Ga was responsible for the emplacement of anorthositic rocks of the LAC along the Cheyenne belt (Fig. 1). This is consistent with the lack of a superposed regional strain field on the magmatic fabrics of the anorthosites (Scoates, 1994), the preservation of magmatic microstructures even in strongly recrystallized rocks (implying small stresses) (Lafrance et al., 1994), and the relatively weak fabric development in the surrounding pelitic and metabasic rocks and granitic gneisses (Grant and Frost, 1990).

Anderson and Bender (1989) and Hoffman (1989) proposed that the mafic melts responsible for the formation of anorthosite were also responsible for causing the large amounts of crustal melting and the formation of the 1.49–1.40 Ga granitic batholiths in the midcontinental U.S. In the western and southwestern U.S., the majority of these granitic batholiths have crystallization ages between 1.43 and 1.44 Ga (summarized in Anderson, 1983; Anderson and Bender, 1989). The anorthositic rocks of the LAC are the only significant exposure of mafic rocks in this area with crystallization ages in this interval. The Sr and Nd isotopic compositions of the anorthositic rocks and associated Al-rich gabbros are consistent with crystallization from mantle-derived magmas that were contaminated by crust during ascent (Scoates and Frost, 1994; Mitchell et al., 1995). If heat from the parental magmas at depth produced the crustal melting required for granite production, then the general absence of exposed mafic magmatism associated with these batholiths may be an artifact of crustal structure (Frost et al., 1993). The LAC may have been allowed to ascend to higher crustal levels along the reactivated Cheyenne belt.

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References cited

Amelin, Y.V., Heaman, L.M., Verchogliad, V.M., and Skobelev, V.M. (1994) Geochronological constraints on the emplacement history of an anorthosite-rapakivi granite suite: U-Pb zircon and baddeleyite study of the Korosten complex, Ukraine. Contributions to Mineralogy and Petrology, 116, 411–419.

Anderson, I.C., Frost, B.R., and Lindsley, D.H. (1987) Crystallization conditions of the Red Mountain syenite. Eos, 68, 442–443.

Anderson, I.C., Geist, D.J., Frost, B.R., and Lindsley, D.H. (1988) Rare earth element depletion during late-stage fractionation, Red Mountain pluton, Laramie anorthosite complex. Eos, 69, 524.

Anderson, J.L. (1983) Proterozoic anorogenic granite plutonism of North America. In Geological Society of America Memoir, 161, 133–154.

Anderson, J.L., and Bender, E.E. (1989) Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States. Lithos, 23, 19–52.

Anderson, J.L., and Morrison, J. (1992) The role of anorogenic granites in the Proterozoic crustal development of North America. In K.C. Condie, Ed., Proterozoic crustal evolution, p. 263–299. Elsevier, Amsterdam.

Ashwal, L.D. (1993) Anorthosites, 422 p. Springer-Verlag, Berlin.

Bolsover, L.R. (1986) Petrogenesis of the Sybille iron-titanium oxide deposit, Laramie anorthosite complex, Laramie Mountains, Wyoming, 78 p. M.S. thesis, State University of New York, Stony Brook, New York.

Bossart, P.J., Meier, M., Oberli, F., and Steiger, R.H. (1986) Morphology versus U-Pb systematics in zircon: A high-resolution isotopic study of a zircon population from a Variscan dike in the Central Alps. Earth and Planetary Science Letters, 78, 339–354.

Butterman, W.C., and Foster, W.R. (1967) Zircon stability and the ZrO_2-SiO_2 phase diagram. American Mineralogist, 52, 880–885.

Chiarenzelli, J.R., and McLelland, J.M. (1993) Granulite facies metamorphism, paleo-isotherms and disturbance of the U-Pb systematics of zircon in anorogenic plutonic rocks from the Adirondack Highlands. Journal of Metamorphic Geology, 11, 59–70.

Doig, R. (1991) U-Pb zircon dates of Morin anorthosite suite rocks, Grenville Province, Quebec. Journal of Geology, 99, 729–738.

Duchesne, J.C., Scharer, U., and Wilmart, E. (1993) A 10 Ma period of emplacement for the Rogaland anorthosites, Norway: Evidence from U-Pb ages. Terra Nova, 5, 64.

Emslie, R.F. (1978) Anorthosite massifs, rapakivi granites, and late Proterozoic rifting of North America. Precambrian Research, 7, 61–98.

——— (1980) Geology and petrology of the Harp Lake complex, Central Labrador: An example of Elsonian magmatism. Geological Survey of Canada Bulletin, 293, 136 p.

Emslie, R.F., and Stirling, J.A.R. (1993) Rapakivi and related granitoids of the Nain Plutonic Suite: Geochemistry, mineral assemblages, and fluid equilibria. Canadian Mineralogist, 31, 821–847.

Epler, N.A. (1987) Experimental study of Fe-Ti oxide ores from the Sybille pit in the Laramie anorthosite, Wyoming, 67 p. M.S. thesis, State University of New York, Stony Brook, New York.

Frost, B.R., Frost, C.D. Lindsley, D.H., Scoates, J.S., and Mitchell, J.N. (1993) The Laramie anorthosite complex and Sherman batholith: Geology, evolution, and theories of origin. In A.W. Snoke, J.R. Steidtmann, and S.M. Roberts, Eds., Geology of Wyoming, p. 119–161. Geological Survey of Wyoming Memoir 5.

Frost, C.D., Meier, M., and Oberli, F. (1990) Single-crystal U-Pb zircon age determination of the Red Mountain pluton, Laramie Anorthosite Complex, Wyoming. American Mineralogist, 75, 21–26.

Fuhrman, M.L., Frost, B.R., and Lindsley, D.H. (1988) Crystallization conditions of the Sybille monzosyenite, Laramie anorthosite complex, Wyoming. Journal of Petrology, 29, 699–729.

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

Gower, C.F., and Tucker, R.D. (1994) Distribution of pre-1400 Ma crust in the Grenville province: Implications for rifting in Laurentia-Baltica during geon 14. Geology, 22, 827–830.

Grant, J.A., and Frost, B.R. (1990) Contact metamorphism and partial melting of pelitic rocks in the aureole of the Laramie anorthosite complex, Wyoming. American Journal of Science, 290, 425–472.

Heaman, L.M., and LeCheminant, A.N. (1993) Paragenesis and U-Pb systematics of baddeleyite (ZrO_2). Chemical Geology, 110, 95–126.

Higgins, M.D., and van Breemen, O. (1992) The age of the Lac-Saint-Jean anorthosite complex and associated mafic rocks, Grenville Province, Canada. Canadian Journal of Earth Sciences, 29, 1412–1423.

Hoffman, P.F. (1989) Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga). Geology, 17, 135–138.

Karlstrom, K.E., and Houston, R.S. (1984) The Cheyenne Belt: Analysis of a Proterozoic suture in southern Wyoming. Precambrian Research, 25, 415–446.

Kolker, A., and Lindsley, D.H. (1989) Geochemical evolution of the Maloin Ranch pluton, Laramie Anorthosite Complex, Wyoming: Petrology and mixing relations. American Mineralogist, 74, 307–324.

Kolker, A., Lindsley, D.H., and Hanson, G.N. (1990) Geochemical evolution of the Maloin Ranch pluton, Laramie Anorthosite Complex, Wyoming: Trace elements and petrogenetic models. American Mineralogist, 75, 572–588.

Kolker, A., Frost, C.D., Hanson, G.N., and Geist, D.J. (1991) Neodymium, strontium, and lead isotopes in the Maloin Ranch pluton, Wyoming: Implications for the origin of evolved rocks at anorthosite margins. Geochimica et Cosmochimica Acta, 55, 2285–2297.

Krogh, T.E. (1973) A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determination. Geochimica et Cosmochimica Acta, 37, 488–494.

Krogh, T.E., and Davis, G.L. (1973) The significance of inherited zircons on the age and origin of igneous rocks: An investigation of the ages of the Labrador adamellites. Carnegie Institution of Washington Year Book, 72, 610–613.

Lafrance, B., John, B.E., and Scoates, J.S. (1994) Submagmatic recrystallization and deformation in the Laramie anorthosite, Wyoming. Eos, 75, 738.

Lindsley, D.H., and Frost, B.R. (1990) Fe-Ti oxide deposits: A part of the "missing" residual liquid from the Laramie anorthosite complex. Geological Society of America Abstracts with Programs, 22, A300.

Loferski, P.J., and Arculus, R.J. (1993) Multiphase inclusions in plagioclase from anorthosites in the Stillwater Complex, Montana: Implications for the origin of the anorthosites. Contributions to Mineralogy and Petrology, 114, 63–78.

Ludwig, K.R. (1988a) PBDAT for MS-DOS, a computer program for IBM-PC compatibles for processing raw Pb-U-Th isotope data, version 1.03. U.S. Geological Survey, Open File Report 88-542.

——— (1988b) ISOPLOT for MS-DOS, a plotting and regression program for radiogenic-isotope data, for IBM-PC compatible computers, version 1.04. U.S. Geological Survey, Open File Report 88-557.

Martignole, J., Machado, N., and Nantel, S. (1993) Timing of intrusion and deformation of the Rivière-Pentecôte anorthosite (Grenville Province). Journal of Geology, 101, 652–658.

McLelland, J.M., and Chiarenzelli, J. (1990) Isotopic constraints on emplacement age of anorthositic rocks of the Marcy massif, Adirondack Mts., New York. Journal of Geology, 98, 19–41.

Mitchell, J.N. (1993) Petrology and geochemistry of dioritic and gabbroic rocks in the Laramie anorthosite complex, Wyoming: Implications for the evolution of Proterozoic anorthosite, 213 p. Ph.D. dissertation, University of Wyoming, Laramie, Wyoming.

Mitchell, J.N., Scoates, J.S., and Frost, C.D. (1995) High-Al gabbros in the Laramie anorthosite complex, Wyoming: Implications for the composition of melts parental to Proterozoic anorthosite. Contributions to Mineralogy and Petrology, 119, 166–180.

Morse, S.A. (1979a) Kiglapait geochemistry: I. Systematics, sampling, and density. Journal of Petrology, 20, 555–590.

——— (1979b) Kiglapait geochemistry: II. Petrography. Journal of Petrology, 20, 591–624.

——— (1986) Convection in aid of adcumulus growth. Journal of Petrology, 27, 1183–1214.

Naslund, H. (1987) Lamellae of baddeleyite and Fe-Cr spinel in ilmenite from the Basistoppen Sill, east Greenland. Canadian Mineralogist, 25, 91–96.

Nyman, M.W., Karlstrom, K.E., Kirby, E., and Graubard, C.M. (1994) Mesoproterozoic contractional orogeny in western North America: Evidence from ca. 1.4 Ga plutons. Geology, 22, 901–904.

Owens, B.E., Dymek, R.F., Tucker, R.D., Brannon, J.C., and Podesek, F.A. (1994) Age and radiogenic isotopic composition of a late- to post-tectonic anorthosite in the Grenville Province: The Labrieville massif, Quebec. Lithos, 31, 189–206.

Paces, J.B., and Miller, J.D., Jr. (1993) Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga midcontinent rift system. Journal of Geophysical Research, 98, 13997–14013.

Parrish, R.R. (1987) An improved micro-capsule for zircon dissolution in U-Pb geochronology. Isotope Geoscience, 66, 99–102.

Rawling, G., Lindsley, D., and Scoates, J. (1995) Baddeleyite (ZrO_2) and plagioclase are incompatible at high *T*: Implications for U-Pb geochronology in anorthosites. V.M. Goldschmidt Conference, abs. vol., p. 82–83.

Scoates, J.S. (1994) Magmatic evolution of anorthositic and monzonitic rocks in the mid-Proterozoic Laramie anorthosite complex, Wyoming, USA, 277 p. Ph.D. dissertation, University of Wyoming, Laramie, Wyoming.

Scoates, J.S., and Frost, C.D. (1994) Magma chamber processes and conduit evolution in the Laramie anorthosite, Wyoming: Sr and Nd isotopes. In Abstracts of the Eighth International Conference on Geochronology, Cosmochronology, and Isotope Geology, U.S. Geological Survey Circular 1107, p. 284.

Smith, J.V., and Newkirk, H.W. (1965) The crystal structure of baddeleyite (monoclinic ZrO_2) and its relation to the polymorphism of ZrO_2. Acta Crystallographa, 18, 983–991.

Stacey, J.S., and Kramers, J.D. (1975) Approximation of terrestrial lead isotope evolution by a two-stage model. Earth and Planetary Science Letters, 26, 207–221.

Subbarayudu, G.V. (1975) The Rb-Sr isotopic composition and the origin of the Laramie anorthosite-mangerite complex, Laramie Range, Wyoming, 109 p. Ph.D. dissertation, State University of New York, Buffalo, New York.

van Breemen, O., and Higgins, M.D. (1993) U-Pb zircon age of the south-west lobe of the Havre-Saint-Pierre anorthosite complex, Grenville Province, Canada. Canadian Journal of Earth Sciences, 30, 1453–1457.

Van Schmus, W.R., Medaris, L.G., and Banks, P.O. (1975) Geology and age of the Wolf River batholith. Geological Society of America Bulletin, 86, 907–914.

Yu, Y., and Morse, S.A. (1993) $^{40}Ar/^{39}Ar$ chronology of the Nain anorthosites, Canada. Canadian Journal of Earth Sciences, 30, 1166–1178.

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