American Mineralogist, Volume 75, pages 13–20, 1990

Sr and Nd isotopic constraints on the origin of the Laramie Anorthosite Complex, Wyoming

Dennis J. Geist
Department of Geology, Hamilton College, Clinton, New York 13323, U.S.A.
Carol D. Frost
Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071, U.S.A.
Allan Kolker*
Department of Earth and Space Sciences, State University of New York, Stony Brook, New York 11794, U.S.A.

Abstract

Anorthosites and gabbros from the Anorthosite Complex (LAC) have Nd and Sr isotopic ratios that are similar to values for undepleted mantle, but variation within the anorthosite-gabbro suite suggests that their isotopic ratios are affected by assimilated country rock. Some of the chemically evolved rocks have isotopic ratios indistinguishable from those of the anorthosites and gabbros, although in general the chemically evolved rocks contain a greater component of crustal material. Each of the chemically evolved satellite intrusions have distinct Sr and Nd isotopic ratios, indicating that each intrusion evolved independently. The isotopic data for the chemically evolved rocks are best explained by assimilation of various amounts of crustal material, followed in some instances by crystal fractionation and further assimilation at the level of emplacement. Isotopic ratios in two oxide-rich rocks are identical to those of the anorthosites, consistent with the hypothesis that they are late-stage fractionates of the anorthosite series.

Introduction

Anorthosite complexes are characterized by features that have perplexed petrologists and geochemists for generations. The principal enigma of anorthosites lies in what kind of magma and processes could have produced the observed vast volumes of nearly monomineralic rock; as Bowen (1917) put forth, the problem with anorthosites is in explaining their mineralogic simplicity. A variety of different types of parental magmas have been proposed, and it is not known whether these magmas come from depleted or pristine mantle or how much crustal material is involved in their genesis (cf. Wiebe, 1980; Morse, 1982; Duchesne, 1984; Emslie, 1985). Furthermore, anorthosites are commonly associated with a ferrodioritic to syenitic to granitic suite (called the "chemically evolved" suite herein) that is characterized by high-temperature, anhydrous mineral assemblages; the relationship between these chemically evolved rocks and the anorthosites is unclear, as is their own internal evolution.

Nd and Sr isotopic studies of anorthosite complexes may help resolve the major problems associated with these enigmatic rocks. First, because the Nd and Sr isotopic compositions of the mantle and old crust are usually distinct, possible sources for the anorthosite suite can be evaluated, in addition to igneous processes such as assimilation, liquid immiscibility, and crystal fractionation. Second, isotopic data may constrain petrogenetic models for the association of the chemically evolved rocks with the anorthosites.

Previous isotopic studies of anorthosite complexes have yielded a variety of results and interpretations. In some cases, anorthosites appear to be uncontaminated mantle-derived rocks (e.g., Ashwal and Wooden, 1983), whereas other studies show isotopic ratios intermediate between those of mantle and crustal material, reflecting significant crustal contamination (Ashwal et al., 1986; Gray, 1987; Menuge, 1988). Some studies have suggested that the associated, chemically evolved rocks are slightly contaminated differentiates of the anorthosites (e.g., Demaiffe and Hertogen, 1981; Morse, 1982; Fuhrman et al., 1988), in sharp disagreement with the alternative interpretation, that the chemically evolved suite is largely the result of crustal anatexis (e.g., Fountain et al., 1981; Duchesne, 1984; Kolker et al., 1990). Most workers agree that the oxide-rich bodies are the result of protracted differentiation of the anorthosite-producing magmas (e.g., Ashwal, 1982) possibly involving liquid immiscibility (Goldberg, 1984).

The Laramie Anorthosite Complex (LAC) in southeastern Wyoming (Fig. 1) is well suited for an isotopic study addressing these problems. Foremost, the LAC has been the subject of collaborative field, petrologic, and geochemical studies for nearly a decade (e.g., Epler et al., 1986; Fuhrman et al., 1988; Kolker and Lindsley, 1989;

* Present address: Department of Applied Science, Brookhaven National Laboratory, Building 815, Upton, New York 11973, U.S.A.

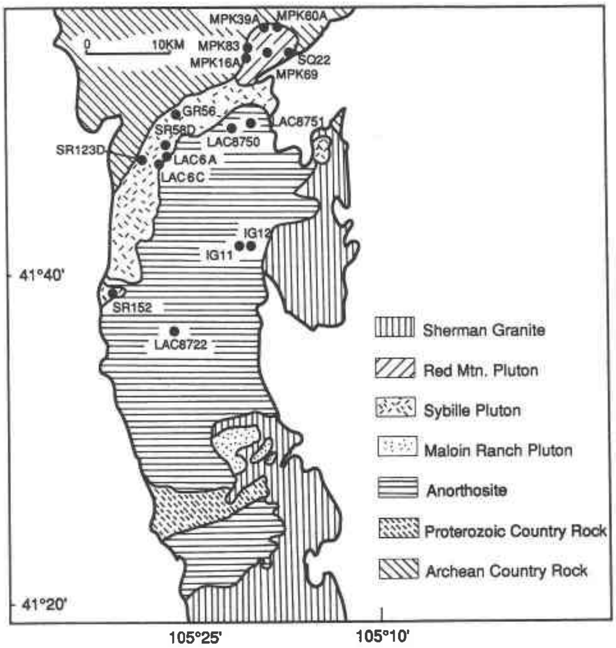

Fig. 1. Simplified geologic map of the Laramie Anorthosite Complex, showing sample locations. Note that many of the units discussed in the text are not mappable at this scale.

Kolker et al., 1990; Anderson et al., 1987, 1988), and large portions of the complex have been mapped at 1:24000. Interpretations based on the isotopic data are therefore constrained by these other types of evidence. Unlike most massif anorthosites in the Grenville province, the LAC is unmetamorphosed and has not been deformed, which makes calculation of initial isotopic ratios more reliable and makes interpretation of geologic and mineralogical data less ambiguous. The LAC is also suitable for isotopic study because the isotopic signatures of the mantle and crust underlying the Laramie Range and adjacent regions have been determined by study of mafic and granitic rocks (Nelson and DePaolo, 1984; Geist et al., 1989). Furthermore, the age of the LAC has been recently established as 1439^{+7}_{-6} Ma by U-Pb study of single zircon crystals from the Red Mountain pluton (Frost et al., 1990), so initial isotopic ratios can be precisely calculated. In addition, previous work (Subbarayudu et al., 1975; Fountain et al., 1981; Kolker et al., 1990) suggests a range of trace-element abundances and Sr isotopic ratios in the different units. Consequently, we have determined Nd and Sr isotopic ratios for well-documented specimens from each of the major units of LAC (Fig. 1).

Geologic overview and sampling

The LAC intruded a major geologic boundary of North America: the Cheyenne belt, a structural zone that separates the Archean Wyoming province to the north from Proterozoic Colorado province to the south (Houston et al., 1979). The Cheyenne belt has been interpreted as a suture between the Archean continental nucleus and Proterozoic island-arc terranes (Duebendorfer and Houston, 1987). To the west of the Laramie Range, the Cheyenne belt is well exposed as a mylonite zone in the Medicine Bow and Sierra Madre Ranges. Within the Laramie Range, the Cheyenne belt is completely obscured by the LAC and Sherman Granite. The nature of the crust underlying and surrounding the LAC is not fully known. Geophysical studies suggest that it is continuous with the Archean rocks to the north of the LAC (Allmendinger et al., 1982; Johnson et al., 1984), whereas isotopic study of Proterozoic granites indicates a dominantly Proterozoic lower and middle crust (Geist et al., 1989). The northernmost part of the LAC intrudes Archean wall rocks. Elsewhere the LAC was emplaced into Early Proterozoic rocks. Both the Archean and Proterozoic country rocks range in composition from orthogneisses to strongly metamorphosed sedimentary rocks.

Anorthositic rocks were emplaced in two main masses that are separated by a septum of Early Proterozoic gneisses and granites. Field observations in the northern lobe of the anorthosite show that it includes several distinct intrusions. The anorthosites are characterized by a very coarse grained protoclastic texture and plagioclase compositions ranging from sodic labradorite through andesine. Interstitial pyroxene occurs in all of the anorthositic rocks, accounting for roughly 5% to 15% of the mode.

Rocks of the chemically evolved suite principally occur in three satellite plutons that intruded the margins of the main lobe of the anorthosite: (1) the Sybille pluton (Fuhrman et al., 1988), (2) the Red Mountain pluton (Anderson et al., 1987, 1988), and (3) the Maloin Ranch pluton (Kolker and Lindsley, 1989; Kolker et al., 1990). Many rocks of the chemically evolved suite are characterized by their anhydrous assemblages, extraordinary Fe enrichment, and K-rich, SiO_2-poor compositions. All of the chemically evolved rocks have intruded anorthosite, and the Red Mountain pluton intrudes the Sybille pluton. Age determinations of zircons in the Maloin Ranch pluton suggests that the age of the Maloin Ranch pluton is similar to that of the other satellite plutons (Subbarayudu et al., 1975; R. E. Zartman, personal communication, 1987).

Each intrusion comprises a variety of rock types. The Maloin Ranch pluton ranges from relatively primitive biotite gabbro and ferrodiorite to fine-grained monzonite to coarse-grained fayalite-bearing monzosyenite and granite. Isotopic data and sample descriptions are reported in Kolker (1989) and Kolker et al. (1990). The Sybille pluton is composed of monzogabbro, monzonite, and monzosyenite. Samples analyzed in this study from the Sybille pluton are described by Fuhrman et al. (1988). Samples SR152 is a monzogabbro that intruded the margin of the Sybille pluton. Samples from the main body of the Sybille pluton, in order of increasing differentiation index, are a fine-grained monzonite (LAC6A), a porphyritic monzonite (LAC6C), and a coarse-grained, granular monzosyenite (SR58D).

The Red Mountain pluton contains the most strongly chemically evolved rocks within the LAC (Anderson et al., 1987, 1988), and analyzed samples include fayalite monzonite (MPK60A), ferrohedenbergite monzonite (MPK83), and granite (SQ22).

Anorthosite samples include LAC8750 from the northern lobe, a felsic layer that is interlayered with more mafic layers. Samples IG11 and IG12 are relatively pure anorthosite samples from the central part of the complex.

Other rock types are volumetrically subordinate to anorthosite and evolved rocks but are petrogenetically important nonetheless. Medium-grained biotite gabbros occur as inclusions and dikes in both the syenitic (GR56) and the anorthosite bodies (LAC8722). Some members of the biotite-gabbro suite are the least chemically evolved rocks of LAC, containing relatively Mg-rich olivine (up to Fo_{65}) and calcic plagioclase (up to An_{64}). The gabbros also contain primary, Ti-rich biotite, which is F- and Cl-bearing, reflecting the water-poor character of the magmas. These rocks are relatively K-rich and would be classified as alkali olivine basalts if they were eruptive. Although some biotite gabbros are relatively chemically evolved, only the most chemically primitive samples were analyzed in this study.

Other minor rock types are related to small, oxide-rich intrusions that are hosted in the anorthosite, including apatite- and Fe-rich troctolites (LAC8751), oxide-rich ferrodiorites (SR123D), and oxide-apatite rocks. These are termed "oxide-rich rocks" herein. On the basis of experimental data and field relations, the oxide-apatite rocks and ferrodiorites are thought to be related to the Fe-rich troctolites by crystal fractionation and liquid immiscibility (Epler et al., 1986). The Fe-rich troctolites are considered by Goldberg (1984) to be fractionates of the anorthosite-producing magma. Oxide-rich ferrodiorites in the Maloin Ranch pluton are thought to be comagmatic with anorthositic rocks, on the basis of field and geochemical evidence (Kolker and Lindsley, 1989)

The Sherman Granite is a voluminous intrusion that is temporally and spatially associated with the LAC (Fig. 1). Like other Proterozoic anorogenic granites, the Sherman Granite is characterized by unusually Fe- and K-enriched compositions. Chemical and mineralogical characteristics of the Sherman Granite are most consistent with crustal melting due to the thermal effects of the intrusion of the LAC-related magmas (Geist et al., 1989). It is possible that part of the Sherman Granite is genetically linked to the LAC suite, as composite dikes that contain both granitic and gabbroic magmas are abundant in the northern part of the LAC (Stafford and Lindsley, 1986). Granitic units also make up part of the Red Mountain and Maloin Ranch plutons. Although zircon ages of the LAC and Sherman Granite are indistinguishable, contact relations indicate that the Sherman Granite intrudes the LAC, suggesting that it is a slightly later magmatic event.

The samples for isotopic analyses were selected to cover each of the major intrusions and lithologic units. Isotopic data for the Sherman Granite are presented in Geist et al. (1989). We have concentrated on the evolved plutons, because they have been well characterized by detailed petrologic and geologic studies (Fuhrman et al., 1988; Anderson et al., 1987; Kolker and Lindsley, 1989; Kolker et al., 1990). In order to compare these rocks with the more primitive members of the LAC, we have also analyzed several anorthositic and gabbroic rocks, which are the subject of a more detailed, ongoing study.

Isotopic results

Representative bulk-rock splits were taken from several kilograms of pulverized rock. Where large fresh samples were not available, smaller samples were obtained by drilling in active creek beds. Approximately 50 mg of finely ground powders were then dissolved, split, and spiked for isotope-dilution analysis. Rb, Sr, Sm, and Nd were extracted and mass spectrometry was performed using techniques described by Geist et al. (1989). Nd isotopic ratios are normalized to $^{146}Nd/^{144}Nd = 0.7219$ and Sr isotopic ratios to $^{88}Sr/^{86}Sr = 0.1194$. Analyses are reported relative to the La Jolla Nd standard of $^{143}Nd/^{144}Nd = 0.511836 \pm 6$ (2σ; $n = 41$) and NBS 987 Sr standard of $^{87}Sr/^{86}Sr = 0.710255 \pm 10$ ($n = 16$). Decay constants of 6.54×10^{-12} and 1.42×10^{-11} were used for Nd and Sr age corrections.

The trace-element data from the isotope-dilution analyses are typical of anorthosite suites. The anorthosites are poor in the incompatible elements Rb, Nd, and Sm and rich in Sr, owing to the accumulation of plagioclase. The oxide-rich rocks contain abundant apatite, which accounts for their high Nd and Sm abundances. The chemically evolved suite has variable trace-element concentrations, owing to accumulation and fractionation of feldspar and trace phases such as apatite, zircon, and monazite, although Sr is notably depleted in the most chemically evolved rocks. Thorough discussions of more complete trace-element data sets are found in Fountain et al. (1981), Kolker et al. (1990), and Anderson (1987, 1988).

The isotopic data do not form a single isochron in either isotopic system. Because the LAC has not been metamorphosed or deformed, the nonisochronous relationship is attributed to varying initial isotopic ratios. The age of the anorthosite has not been directly determined; however, because syenite from the Red Mountain pluton is 1439^{+7}_{-6} Ma (Frost et al., 1990) and geologic evidence attests to a close temporal link between all members of the LAC, all initial ratios are calculated for 1.44 Ga.

Initial ϵ_{Nd} values for the LAC range from +2.1 to −4.4 (Table 1 and data of Kolker, 1989; Fig. 2). These values are all lower than the +3 to +6 values from presumed mantle-derived rocks from the Proterozoic Colorado province (Nelson and DePaolo, 1984) and overlap almost completely with the range for Proterozoic granitoids from the Laramie Range (Geist et al., 1989). The LAC data fall within the range determined for anorthosites of eastern North America (Ashwal and Wooden, 1985), indicating that it is typical of Proterozoic anorthosite massifs.

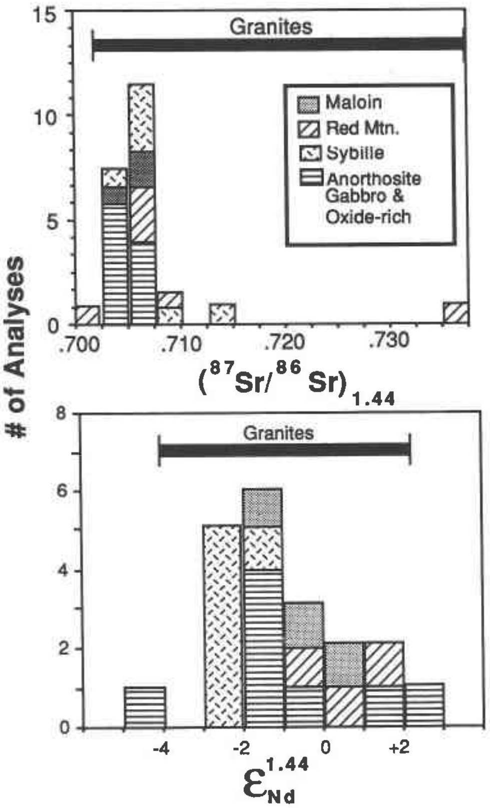

Fig. 2. Histogram showing the range of initial isotopic ratios of the different plutons of the Laramie Anorthosite Complex. In addition to the data reported herein, data for a gabbro, a Sybille syenite, two anorthosites, and the Maloin Ranch pluton come from Kolker (1989) and data for the Red Mountain pluton come from Anderson et al. (1987, 1988).

Each intrusion, including the anorthosite, displays measurable Nd isotopic heterogeneity (Fig. 2).

Initial $^{87}Sr/^{86}Sr$ ratios of LAC rocks show much greater diversity than the Nd data, ranging from 0.7037 to 0.7360 (Table 1 and data in Kolker, 1989; Fig. 2). It should be noted that the error in the calculations of initial Sr isotopic ratios for some of the chemically evolved rocks is quite high (up to 0.022), owing to exceedingly high Rb/Sr ratios and the age of these rocks. Furthermore, many of these rocks are lightly seriticized, which may affect the Rb-Sr isotopic system. Despite these uncertainties, it is clear that the Sr isotopic values of the LAC suite overlap with those of the Sherman Granite (Fig. 2). Furthermore, each of the chemically evolved intrusions displays notable Sr isotopic heterogeneity, but the anorthosites and gabbros have a very small range in initial $^{87}Sr/^{86}Sr$.

An/(An + Ab) ratios are used as an index of differentiation for these rocks, owing to the cumulate nature of some of the coarse-grained rocks and the abundance of plagioclase. Because different analytical techniques have been utilized, three types of data are used in the calculation of An/(An + Ab): (1) microprobe data from plagioclase, (2) microprobe data recombined from exsolved ternary feldspars, and (3) normative abundances from bulk-rock analyses. There is no apparent correlation between the initial Sr and Nd isotopic ratios and the An/(An + Ab) ratios throughout the entire complex, but the most radiogenic values are restricted to the chemically evolved suite (Fig. 3). The individual intrusions show contrasting behavior. The Sr isotopic ratios of Red Mountain rocks increase and the Nd isotopic ratios decrease regularly with the sequence fayalite syenite to ferrohedenbergitic syenite to granites. There is no simple relation between the isotopic ratios and evolution in the Sybille pluton. For ex-

Table 1. Isotopic data

Sample	Latitude (N)	Longitude (W)	[Rb]	[Sr]	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Anorthosites and gabbros						
LAC8722	41°36′57″	105°26′08″	2.852	653.7	0.0126	0.704008(22)
LAC8750	41°46′03″	105°22′02″	8.624	1186	0.0210	0.705226(21)
IG11	41°41′30″	105°20′31″	7.908	1441	0.0159	0.705472(21)
GR56	41°47′18″	105°26′28″	14.70	427.8	0.0994	0.707873(32)
IG12	41°41′23″	105°20′06″	6.194	986.0	0.0182	0.705579(20)
Oxide-rich rocks						
LAC8751	41°46′45″	105°20′50″	4.275	383.0	0.0323	0.706180(21)
SR123D	41°43′21″	105°27′51″	4.775	440.3	0.0314	0.706345(28)
Sybille pluton						
SR58D	41°44′30″	105°26′16″	42.90	499.4	0.2486	0.711060(22)
SR152	41°38′12″	105°29′14″	2.686	714.8	0.0109	0.704742(24)
LAC6A	41°44′01″	105°26′30″	20.78	675.7	0.0890	0.714934(26)
LAC6C	41°44′00″	105°26′46″	10.54	790.0	0.0386	0.707247(27)
Red Mountain pluton						
MPK60a	41°53′49″	105°16′19″	149.6	564.1	0.768	0.720924(14)
MPK83	41°53′06″	105°18′04″	156.7	47.13	9.813	0.912622(15)
SQ22	41°53′05″	105°14′13″	220.1	25.62	26.24	1.278122(48)

Note: Initial isotopic ratios are reported for 1.44 Ga; 2σ uncertainties are in parentheses. Analytical details are in text.

ample, the least chemically evolved fine-grained monzonite (LAC-6A) has the most crustallike isotopic ratios, whereas more chemically evolved coarse-grained monzosyenites have more primitive isotopic ratios. There is also no simple relationship between the chemical evolution of the rocks of the Maloin Ranch pluton and their isotopic ratios (Kolker et al., 1990). These observations suggest that whereas assimilation increased with magma evolution in the small Red Mountain pluton, in the larger, more complex Sybille and Maloin Ranch plutons, assimilation is decoupled from magmatic differentiation. Instead, the amount of assimilation may depend upon the distance to the country-rock contact or the relative order of emplacement.

Covariation between initial Nd-Sr isotopic ratios offers the greatest insight into the relation between the different lithologic and intrusive units (Fig. 4). The most important observations gleaned from Figure 4 are as follows: (1) Each intrusion forms a different field on this diagram, and each intrusion has discernible isotopic heterogeneity. (2) In general, the chemically evolved rocks have more radiogenic Sr isotopic ratios than the anorthosites and gabbros, although the most isotopically primitive syenitic rocks overlap the field containing the anorthosites and gabbros. (3) There is complete overlap of the LAC suite with Proterozoic granitoids of the southern Laramie Range. Furthermore, the data both from the anorthosites and gabbros and from the chemically evolved suites extend to distinctly crustal isotopic values. (4) The anorthosites and gabbros form a nearly vertical trend on this diagram, and the chemically evolved rocks form more nearly horizontal trends. In other words, the anorthosite-gabbro suite has little variation in initial Sr isotopic ratios and large variation in ϵ_{Nd}, and these relations are reversed in the chemically evolved suite. (5) The two oxide-rich samples are isotopically indistinguishable and similar to the anorthosites and gabbros, consistent with the conclusions of previous work (Goldberg, 1984) that the rocks are genetically related.

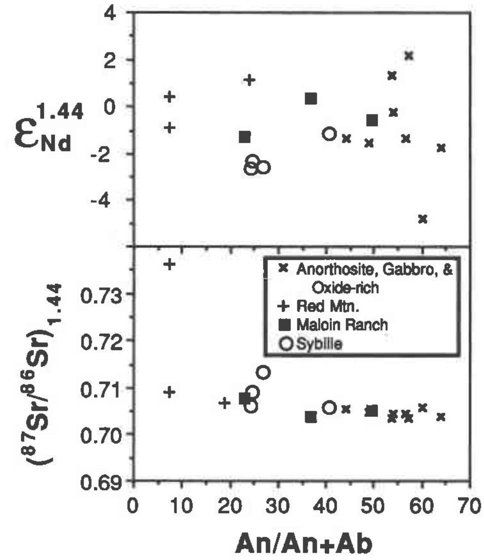

Fig. 3. Relationship between the evolution of LAC rocks [An/(An + Ab) ratios] and their isotopic ratios. Mineral data are from Fuhrman et al. (1988), Kolker and Lindsley (1989), I. C. Anderson (personal communication), Epler et al. (1986), and our unpublished data.

Discussion

The most likely candidate for the parental magma of the LAC are the biotite gabbros that make up a small but

Table 1—*Continued*

I_{Sr}	[Sm]	[Nd]	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\epsilon_{1.44}$
0.7037(20)	1.260	5.648	0.1349	0.511964(21)	−1.7(0.4)
0.7047(20)	1.074	5.701	0.1139	0.511774(25)	−1.6(0.5)
0.7051(20)	0.748	4.422	0.1022	0.511564(34)	−3.5(0.7)
0.7058(20)	2.154	10.80	0.1206	0.511672(16)	−4.8(0.3)
0.7052(20)					
0.7055(20)	37.84	180.4	0.1268	0.511907(11)	−1.4(0.2)
				0.511897(24)	
0.7056(20)	19.44	96.27	0.1221	0.511873(16)	−1.2(0.3)
0.7059(20)	6.919	33.04	0.1266	0.511840(15)	−2.6(0.3)
0.7045(20)	4.055	16.84	0.1456	0.512008(21)	−2.9(0.4)
0.7130(20)	19.62	97.25	0.1220	0.511797(19)	−2.6(0.4)
0.7064(20)	12.62	60.47	0.1262	0.511841(19)	−2.5(0.4)
0.7050(20)	29.66	155.9	0.1150	0.511923(28)	+1.1(0.6)
0.7099(32)	119.0	731.1	0.0984	0.511663(20)	−0.9(0.4)
0.7360(220)	54.86	247.5	0.1340	0.512066(21)	+0.4(0.4)

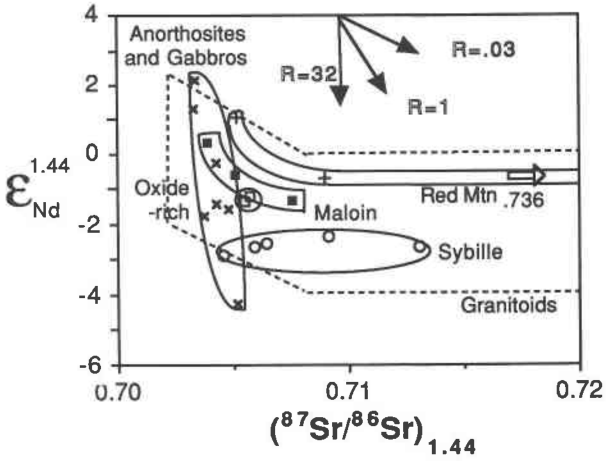

Fig. 4. Sr and Nd isotopic variation of the different plutons of the Laramie Anorthosite Complex, including data from Kolker (1989). Top inset shows the variation predicted for different values of *R*, which is the ratio of Sr/Nd in the parent to Sr/Nd in the contaminant. The $R = 32$ and $R = 0.03$ curves are calculated by mixing anorthosite and evolved syenite from the Red Mountain pluton, respectively, with crustal material having 300 ppm Sr and 60 ppm Nd and the isotopic ratios of a Laramie Range Archean gneiss (Geist et al., 1989).

widespread part of the complex; some of these rocks have the least chemically evolved feldspars and mafic minerals found within the LAC. They are clearly not primary mantle melts, however, owing to their low MgO/(MgO + FeO) ratios and Cr and Ni contents (Kolker et al., 1990; Geist, unpublished data). The biotite gabbros are also important because they overlap in isotopic ratios and plagioclase compositions with the anorthosites (Fuhrman et al., 1988; Kolker et al., 1990). These features point to a genetic link between these two lithologic units.

The isotopic data do not uniquely define the sources for the biotite gabbros and anorthosites. The relatively low ϵ_{Nd} values of both units clearly rule out depleted mantle as their sole precursor, as do their relatively high $^{87}Sr/^{86}Sr$ ratios. This leaves two possibilities: (1) the parental magmas were generated from depleted mantle and were subsequently contaminated by continental crust, or (2) the parental magmas were generated from a relatively heterogeneous, undepleted mantle source and are mostly unaffected by contamination.

Anorthosites are highly susceptible to contamination by crustal Nd owing to their low Nd concentrations (Ashwal et al., 1986). In the case of the LAC, it is impossible to determine the exact extent of contamination in either the anorthosites or the evolved rocks, owing to the isotopically heterogeneous crust in this area (Geist et al., 1989). However, the *variability* within the anorthosite-gabbro suite is best explained by crustal contamination (see below), suggesting that contamination may have also affected the most isotopically primitive rocks.

The notable isotopic heterogeneity of each monzosyenitic intrusion indicates that they evolved through open-system processes, involving assimilation that took place during crystallization of the plutons and mixing of separate batches of magma derived from distinct sources. Petrographic observations and trace- and major-element evidence from the Maloin Ranch pluton indicate that mixing of magmas from different sources controlled the evolution of that intrusion (Kolker and Lindsley, 1989; Kolker et al., 1990). Trace-element data and the existence of partly digested xenoliths and abundant xenocrysts in the Sybille and Red Mountain plutons suggest that emplacement-level assimilation was important in their evolution (Fountain et al., 1981; Fuhrman et al., 1988; Anderson et al., 1987, 1988). It is also clear that the anorthosite evolved by open-system differentiation, because there are many intrusive contacts within the anorthosite, and anorthosite-within-anorthosite xenoliths are observed. Also, partly digested country-rock xenoliths are contained in the border facies of the anorthosite.

The fact that each of the chemically evolved intrusions forms a different field on the Sr-Nd isotopic covariation diagram indicates that the parental magmas for each intrusion had distinct Nd isotopic ratios. The data also suggest that the amount of assimilation was different in the different intrusions. For example, the Red Mountain pluton is the most strongly chemically evolved body in the LAC, and it also has the highest initial $^{87}Sr/^{86}Sr$ ratios, suggesting that it has experienced the greatest amount of high-level assimilation. There is also a general correlation between the internal chemical evolution of the Red Mountain pluton, as measured by the differentiation indices of the individual samples, and its initial Sr isotopic ratios, further suggesting assimilation coupled with fractional crystallization at shallow levels. These interpretations are consistent with field evidence and trace- and major-element data (Anderson et al., 1987, 1988). On the other hand, there is no correlation between the extent of differentiation and the isotopic ratios in the Sybille pluton, even though it intruded a similar geologic environment as that of the Red Mountain pluton (the anorthosite–Archean gneiss contact). The Maloin Ranch pluton also shows no simple relation between initial isotopic ratios and the degree of chemical evolution. The difference in isotopic ratios between the Sybille pluton and the Maloin Ranch pluton may be explained by the fact that the Maloin Ranch pluton intrudes Proterozoic rocks, whereas the Sybille pluton intrudes Archean wall rocks. Trace-element and petrographic evidence suggests that several magmas having different source characteristics coexisted in the Maloin Ranch pluton (Kolker et al., 1990), an interpretation consistent with the isotopic data. However, this hypothesis is difficult to reconcile with the isotopic data from the Red Mountain pluton, which intrudes Archean country rock yet does not show evidence of extensive contamination by Archean material. It is possible that the Red Mountain magmas were shielded from interaction with the wall rocks by ascent through chemically insulated conduits developed by Sybille magmas.

The observation that each of the chemically evolved intrusions has a distinct range in isotopic ratios also proves that the intrusions evolved independently. However, the continuous and similar range of the mineral compositions within the intrusions (Fuhrman et al., 1988) suggests that they could have evolved along similar liquid lines of descent from similar parental magmas. One possible explanation is that the major-element compositions of the magmas were controlled by fractional crystallization, whereas the trace-element and isotopic evolution was largely controlled by variable amounts of contamination by different crustal materials. This hypothesis is supported by the fact that the LAC is clearly more contaminated around its margin (field observation; Fountain et al., 1981), a process that has affected trace-element and isotopic values drastically but did not alter the mineral chemistry very strongly (Fuhrman et al., 1988). Alternatively, Kolker et al. (1990) have proposed that the different units in the Maloin Ranch pluton came from noncomagmatic melts derived from different crustal sources.

The vertical trend that the anorthosites and gabbros form on the Sr-Nd isotopic correlation diagram (Fig. 4) is best explained by contamination of anorthosite, which has a very high Sr/Nd ratio, with crustal material having a low Sr/Nd ratio compared to anorthosite. Conversely, the subhorizontal fields of the evolved plutons can be explained by their relatively low Sr/Nd ratios. This cannot be the only factor controlling this trend, however, as there is no simple relationship between the Sr concentration and the initial $^{87}Sr/^{86}Sr$ ratios within these intrusions. The Sr isotopic heterogeneity of the crust in the southern Laramie Range and the relative Nd isotopic homogeneity (Geist et al., 1989) also may contribute to the horizontal trend formed by the satellite plutons.

Conclusions

The isotopic ratios of the anorthosites and gabbros and the isotopic variation within that suite suggest that these rocks have experienced crustal contamination, as opposed to being generated from relatively enriched mantle sources. These two possibilities are of course not exclusive, which presents problems in using anorthosites as tracers of the kind of mantle present beneath regions of continental crust. We note, however, that most of the isotopic variation among the anorthosite samples is the result of contamination by crustal material with a relatively low Sr/Nd ratio. This would suggest that all of the anorthosites and gabbros have been contaminated to some degree, although this question is not resolvable with these data.

The isotopic data also show that the LAC is a distinctively composite intrusion. In other words, the LAC is made up of many individual intrusions that evolved independently by different processes and in different environments. For example, it is clear that the Red Mountain pluton is not simply a fractionate derived from the Sybille pluton. Moreover, the anorthosite itself is made up of several different intrusions that were variably contaminated, and it is therefore not a simple, homogeneous body.

It is possible that the chemically evolved suite could be entirely derived from crustal melts, as it has isotopic ratios indistinguishable from those of the granites in this area. This interpretation would be consistent with that of Kolker et al. (1990), who proposed that most of the different units of the chemically evolved suite are noncomagmatic and the result of melting of different crustal sources. Alternatively, the chemically evolved suite could be a late-stage differentiate of the gabbroic magmas that were contaminated during crystal fractionation. This interpretation is consistent with that of Fuhrman et al. (1988), who observed that the variation in mineral chemistry is continuous from the gabbros and anorthosites through the chemically evolved rocks and that the chemically evolved rocks are more contaminated around their margin (Fountain et al., 1981; Subbarayudu et al., 1975). The data presented herein indicate that the evolution of these rocks is much more complex, however. For example, sample LAC6A, a fine-grained monzonite, lies well inside the margins of the LAC but has the highest initial $^{87}Sr/^{86}Sr$ for the Sybille pluton. Apparently, parts of the Sybille pluton were contaminated at deeper levels or were derived from different sources. Because of the small isotopic contrast between the LAC suite and the crust in this region and the strongly heterogeneous nature of the crust in the Laramie Range (Geist et al., 1989), it is not possible to quantify the amount of assimilation that has taken place in the individual intrusions and the nature of the mantle that has produced the most primitive rocks. However, it has been shown conclusively that some assimilation has taken place in the development of both the anorthosite and the chemically evolved suite.

The similarity in the isotopic data from the two oxide-rich rocks from the northern part of the LAC provides permissive evidence that some oxide-rich rocks are differentiates of the anorthosite-producing magmas (cf. Ashwal, 1982; Goldberg, 1984) that separated into immiscible liquids. Melting experiments and field relations also support the hypothesis that these rocks are related by liquid immiscibility (Epler et al., 1986). The interpretation that they are comagmatic is also consistent with the data for oxide-rich ferrodiorite of the Maloin Ranch pluton (Kolker et al., 1990).

Acknowledgments

We thank I. C. Anderson, D. H. Lindsley, and M. L. Fuhrman for providing their samples for isotopic study. We also thank Lindsley, Anderson, and B. R. Frost for discussion of the geologic relations of these rocks and D. Unruh and L. D. Ashwal for their reviews. The work was completed while Geist held an NSF-supported postdoctoral research position at the University of Wyoming (NSF grant EAR-8617812 awarded to B. R. Frost and C. D. Frost).

References Cited

Allmendinger, R.W., Brewer, J.A., Brown, L.D., Kaufman, S., Oliver, J.E., and Houston, R.S. (1982) COCORP profiling across the Rocky Mountain Front in southern Wyoming, Part 2: Precambrian basement structure and its influence on Laramide deformation. Geological Society of America Bulletin, 93, 1253–1263.

Anderson, I.C., Frost, B.R., and Lindsley, D.H. (1987) Crystallization conditions of the Red Mountain Syenite, Laramie Anorthosite Complex, Wyoming. EOS, 68, 442.

Anderson, I.C., Geist, D.J., Frost, B.R., and Lindsley, D.H. (1988) Rare earth depletion during late stage fractionation, Red Mountain pluton, Laramie Anorthosite Complex, Wyoming. EOS, 69, 524.

Ashwal, L.D. (1982) Mineralogy of mafic and Fe-Ti oxide-rich differentiates of the Marcy anorthosite massif, Adirondacks, New York. American Mineralogist, 67, 14–27.

Ashwal, L.D., and Wooden, J.L. (1983) Isotopic evidence from the eastern Canadian shield for geochemical discontinuity in the Proterozoic mantle. Nature, 306, 679–680.

——— (1985) Sm-Nd isotopic studies of Proterozoic anorthosites: Systematics and implications. In A.C. Tobi and J.L.R. Touret, Eds., The deep Proterozoic crust in the North Atlantic provinces, p. 61–73. Reidel, Boston.

Ashwal, L.D., Wooden, J.L., and Emslie, R.F. (1986) Sr, Nd, and Pb isotopes in Proterozoic intrusives astride the Grenville Front in Labrador: Implications for crustal contamination and basement mapping. Geochimica et Cosmochimica Acta, 50, 2571–2585.

Bowen, N.L. (1917) The problem of the anorthosites. Journal of Geology, 25, 209–243.

Demaiffe, D., and Hertogen, J. (1981) Rare earth element geochemistry and strontium isotopic composition of a massif-type anorthosite-charnockite body: The Hidra massif (Rogaland, SW Norway). Geochimica et Cosmochimica Acta, 45, 1545–1561.

Duchesne, J.-C. (1984) Massif anorthosites: Another partisan review. In W.L. Brown, Ed., Feldspars and feldspathoids, p. 411–433. Reidel, Boston.

Duebendorfer, E.M., and Houston, R.S. (1987) Proterozoic accretionary tectonics at the southern margin of the Archean Wyoming craton. Geological Society of America Bulletin, 98, 554–568.

Emslie, R.F. (1985) Proterozoic anorthosite massifs. In A.C. Tobi and J.L.R. Touret, Eds. The deep Proterozoic crust in the North Atlantic provinces, p. 39–60. Reidel, Boston.

Epler, N.E., Bolsover, L.R., and Lindsley, D.H. (1986) Experimental study of the origin of the Sybille Fe-Ti oxide deposit, Laramie Anorthosite Complex, SE Wyoming. Geological Society of America Abstracts with Programs, 18, 595.

Fountain, J.C., Hodge, D., and Hills, F.A. (1981) Geochemistry and petrogenesis of the Laramie Anorthosite Complex. Lithos, 14, 113–132.

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, 000–000.

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.

Goldberg, S.A. (1984) Geochemical relationships between anorthosite and associated iron-rich rocks, Laramie Range, Wyoming. Contributions to Mineralogy and Petrology, 87, 376–387.

Gray, C.M. (1987) Strontium isotopic constraints on the origin of Proterozoic anorthosites. Precambrian Research, 37, 173–189.

Houston, R.S., Karlstrom, K.E., Hills, F.A., and Smithson, S.B. (1979) The Cheyenne belt: A major Precambrian crustal boundary in the western United States. Geological Society of America Abstracts with Programs, 11, 446.

Johnson, R.A., Karlstrom, K.E., Smithson, S.B., and Houston, R.S. (1984) Gravity profiles across the Cheyenne belt, a Precambrian crustal suture in southeastern Wyoming. Journal of Geodynamics, 1, 445–472.

Kolker, A. (1989) Petrology and geochemical evolution of the Maloin Ranch pluton, Laramie Anorthosite Complex, Wyoming. Ph.D. dissertation, State University of New York, Stony Brook, New York.

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, 000–000.

Menuge, J.F. (1988) The petrogenesis of massif anorthosites: A Nd and Sr isotopic investigation of the Proterozoic of Rogaland/Vest-Agder, SW Norway. Contributions to Mineralogy and Petrology, 98, 363–373.

Morse, S.A. (1982) A partisan review of Proterozoic anorthosites. American Mineralogist, 67, 1087–1100.

Nelson, B.K., and DePaolo, D.J. (1984) 1,700-Myr greenstone volcanic successions in southwestern North America and isotopic evolution of Proterozoic mantle. Nature, 312, 143–146.

Stafford, J.M., and Lindsley, D.H. (1986) Characterization of mixing between biotite gabbro and granite in the Laramie Anorthosite Complex. EOS, 67, 385.

Subbarayudu, G.V., Hills, F.A., and Zartman, R.E. (1975) Age and Sr isotopic evidence for the origin of the Laramie anorthosite-syenite complex, Laramie Range, Wyoming. Geological Society of America Abstracts with Programs, 7, 1287.

Wiebe, R.A. (1980) Anorthositic magmas and the origin of Proterozoic anorthosite massifs. Nature, 286, 564–567.

Manuscript received February 20, 1989
Manuscript accepted September 29, 1989