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Primitive and Contaminated Basalts from the Southern Rocky Mountains, U.S.A.*

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Abstract. Basalts in the Southern Rocky Mountains province have been analyzed to determine if any of them are primitive. Alkali plagioclase xenocrysts armored with calcic plagioclase seem to be the best petrographic indicator of contamination. The next best indicator of contamination is quartz xenocrysts armored with clinopyroxene. On the rocks and the region studied, K_2O apparently is the only major element with promise of separating primitive basalt from contaminated basalt inasmuch as it constitutes more than 1% in all the obviously contaminated basalts. K_2O: lead (>4 ppm) and thorium (>2 ppm) contents and Rb/Sr (>0.035) are the most indicative of the trace elements studied. Using these criteria, three basalt samples are primitive (although one contains 1.7% K_2O) and are similar in trace-element contents to Hawaiian and Eastern Honshu, Japan, primitive basalts.

Contamination causes lead isotope ratios, $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, to become less radiogenic, but it has little or no effect on $^{87}Sr/^{86}Sr$. We interpret the effect on lead isotopes to be due to assimilation either of lower crustal granitic rocks, which contain 5—10 times as much lead as basalt and which have been low in U/Pb and Th/Pb since Precambrian times, or of upper crustal Precambrian or Paleozoic rocks, which have lost much of their radiogenic lead because of heating prior to assimilation. The lack of definite effects on strontium isotopes may be due to the lesser strontium contents of granitic crustal rocks relative to basaltic rocks coupled with lack of a large radiogenic enrichment in the crustal rocks.

Lead isotope ratios were found to be less radiogenic in plagioclase separates from an obviously contaminated basalt than in the primitive basalts. The feldspar separate that is rich in sodic plagioclase xenocrysts was found to be similar to the whole-rock composition for $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ whereas a more dense fraction probably enriched in more calcic plagioclase phenocrysts is more similar to the primitive basalts in lead isotope ratios.

The primitive basalts have: $^{206}Pb/^{204}Pb \sim 18.09$—$18.34$, $^{207}Pb/^{204}Pb \sim 15.5$, $^{208}Pb/^{204}Pb \sim 37.6$—$37.9$, $^{87}Sr/^{86}Sr \sim 0.704$—$0.705$. In the primitive basalts from the Southern Rocky Mountains the values of $^{206}Pb/^{204}Pb$ are similar to values reported by others for Hawaiian and eastern Honshu basalts and abyssal basalts, whereas $^{208}Pb/^{204}Pb$ tends to be equal to or a little less radiogenic than those from the oceanic localities. $^{87}Sr/^{86}Sr$ appears to be equal to or a little greater than those of the oceanic localities. These $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios are distinctly less radiogenic and $^{87}Sr/^{86}Sr$ values are about equal to those reported by others for volcanic islands on oceanic ridges and rises.

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Introduction

Little attention has been paid to the volumetrically minor but widespread Cenozoic basalts of the Rocky Mountain provinces, probably because of the possibility of crustal contamination. Yet understanding of these basalts is necessary to help answer such genetic questions as whether the source of basalt magma is the same for the continents as for the ocean basins. Therefore, we have attempted to find basalts in the Rocky Mountains that are uncontaminated by silicic crust and to determine the effects of contamination on element concentration and isotopic composition.

The criteria used to distinguish uncontaminated (primitive) basalts from their contaminated companions are the presence of xenocrysts, a comparison of major and trace element concentrations with those in Hawaiian and abyssal basalts, and the presence of the radiogenic tracers lead and strontium. We regard any basalt that contains quartz xenocrysts to be contaminated. Quartz often persists because it reacts with the basalt magma to form an armor of clinopyroxene. The presence of sodic plagioclase (armored from the melt by a rim of calcic plagioclase) also suggests contamination, but it is not conclusively indicated because of the possibility of cognate crystallization from a basalt magma under high pressure (Cohen, Ito, and Kennedy, 1967). In crustal contamination of a basalt, certain major and trace elements that are enriched in rocks of granitic composition may increase in abundance. In this paper we are concerned primarily with contents of K_2O, SiO_2, U, Th, Pb, Rb, and Sr and with the ratios of trace elements pertinent to the radiogenic tracers—U/Pb, Th/U, and Rb/Sr. We realize that crustal contamination may well parallel differentiation trends; however, if these elemental contents and relevant element ratios of continental basalts are similar to those of basalts on oceanic islands or of abyssal basalts (deep ocean tholeiites), then the continental basalt is a good candidate to be as primitive as are the oceanic basalts. As the identification of primitive basalts relies upon the absence of criteria of contamination, crustally contaminated basalts may be identified with much greater certainty than may their uncontaminated parents. We therefore prefer to use the less definite term "primitive basalts" rather than "uncontaminated basalts" for those for which we can find no criteria of contamination.

Emphasized here are two suites of basalts, each suite presumably representing outpourings from a restricted source area over a short period of time: Hinsdale formation of Pliocene age (Lipman and Mehnert, 1968) from the San Juan volcanic area in southern Colorado, and basalts of the Servilleta Formation of Montgomery (1953), latest Pliocene in age (Ozima *et al.*, 1967), from northern NewMexico with chemistry and petrography from Aoki (1967). Subsequent field work has shown that the two contaminated samples of the Servilleta Formation may be related to Hinsdale basalt. We have kept this possibility in mind when we formed our conclusions. Some miscellaneous samples from Colorado and New Mexico are also included to provide regional information. Most important among these is the contaminated-primitive pair from the Jemez Mountains, New Mexico. Visual estimates of mineral abundances in the basalts are given in Appendix A. Most samples are near the boundary of tholeiites and olivine tholeiites or alkali basalt. Plagioclase is predominantly in the range An_{50-60} but some xenocrysts have cores down to An_{20} (66L20). The rocks are all as fresh as could be obtained from surface samples. Some samples have olivine with only slight alteration to iddingsite (65L120, A54-14, J54-4 and 54P152), but others grade toward and may be mostly iddingsite (66L26 and 65L32). The iddingsite may be a deuteric effect.

Analytical Techniques

Mineral Identification. The phases were identified by conventional petrographic examination of one thin section per sample except for the Servilleta Formation for which Aoki (1967) also gives petrographic description.

Major Elements. Whole-rock chemical analyses were obtained by rapid rock colorimetric methods (Shapiro and Brannock, 1956) or by standard gravimetric methods (Peck, 1964). The analysts are given in Appendix B.

Minor Elements. Lead, uranium, and thorium contents are determined by stable isotope dilution. The isotopic compositions are determined by mass spectrometry. Cubes of basalt from the insides of the samples are taken by diamond sawing. Lead contamination from this step is negligible. The cubes are cleaned ultrasonically in distilled water, dried in an oven, and pulverized in a Diamond steel mortar. Contamination from this step was estimated by pulverizing optical quartz. The lead added in the process is ≤ 0.05 ppm (this figure includes the lead content of the quartz). As a basalt is a softer material than quartz, the lead contamination of basalt is expected to be less than the quartz value; therefore, at the concentration levels encountered, less than 2.5% of the determined lead should come from the mechanical phases of the analysis. Contamination of the other relevant elements is negligible.

The Pb, U, and Th concentrations are measured by isotope dilution using a combined spike of the enriched isotopes ^{206}Pb, ^{235}U, ^{230}Th on a portion of sample split through pure aluminium splitters (Servilleta basalts) or poured from a bottle to minimize possible contamination steps. A repeat analysis on 6L26 showed Pb, U, and Th to be heterogeneously distributed probably due to non-ideal sample splitting; however, the important values of $^{238}U/^{204}Pb$ and $^{232}Th/^{238}U$ remain unchanged. To obtain better reproducibility, the Servilleta basalt samples and a reanalysis of 66L20 were split as stated. The trace elements are purified by HF-$HClO_4$ dissolution followed by a $Ba(NO_3)_2$ coprecipitation of lead from concentrated nitric acid followed by a dithizone solution extraction (Tatsumoto, 1966a); the nitric acid supernate contains the uranium and thorium which are purified together on a nitrate anion resin column (Tatsumoto, 1966a). The isotopic composition of the spiked samples are determined on mass spectrometers by techniques described by Doe, Tatsumoto, Delevaux, and Peterman (1967) for lead, and by Rosholt, Doe, and Tatsumoto (1966) for uranium and thorium. The analytical uncertainties of concentrations, except for sample splitting, is 3%. The purification of lead for isotopic composition is done by the volatilization method of Masuda as modified by Tatsumoto (1966a) for 5L120, 6L20, 6L26, 6561304, and 6561501, and by the HF-$HClO_4$ dissolution method of Tilton as modified by Tatsumoto (1966a) for $Ba(NO_3)_2$ coprecipitation and the additional steps given by Doe, Tatsumoto, Delevaux, and Peterman (1967) for sample 6561302. As the contaminated basalts could be internally isotopically heterogeneous, the HF-$HClO_4$ dissolution on 6561302 was made to check whether the volatilization extractions gave lead representative of the whole rock. We conclude that it does from the isotopic identity of 6561302 with 6561501. The plagioclases were analyzed by conventional HF-$HClO_4$ dissolution, ion column, and dithizone extraction methods. The same mass spectrometers are used for isotopic composition and concentration measurements. The standard deviations, expressed as percent of a ratio, are: 0.29 for $^{206}Pb/^{204}Pb$, 0.37 for $^{207}Pb/^{204}Pb$ and 0.47 for $^{208}Pb/^{204}Pb$.

Strontium for isotopic composition is purified by conventional HF-H_2SO_4 and chloride cation resin techniques modified from Aldrich and Davis and analyzed as reported by Peterman, Doe, and Bartel (1967). All values of $^{87}Sr/^{86}Sr$ are precise to ± 0.0006 at twice the standard deviation. Rb and Sr concentrations are determined by X-ray fluorescence calibrated with basalts analyzed by isotope dilution. The uncertainty in the concentrations is about 15%; however, the values of Rb/Sr have an uncertainty of only about 3% at twice the standard deviation because many absorption and enhancement effects are compensating for these two elements.

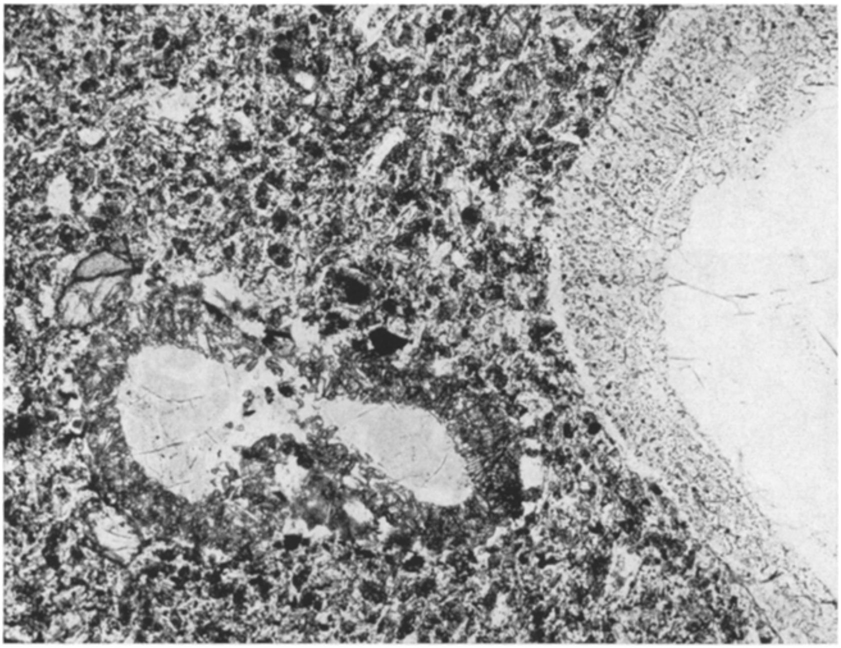

Fig. 1. Photomicrograph (50×) of a contaminated basalt showing a large sodic plagioclase xenocryst (on the right) and wormy reaction rim and a large dumbbell-shaped quartz xenocryst with clinopyroxene armor (in lower center)

Xenocrysts

To determine whether a basalt is contaminated, first the basalts are classified by the presence or absence of xenocrysts—quartz and sodic plagioclase (Appendix A). The possibility that these plagioclases are high-pressure phenocrysts is judged by isotopic methods in the isotope section. Sodic plagioclase armored by calcic plagioclase (Fig. 1) appears in all our identifiably contaminated basalts. Quartz armored by clinopyroxene also appears in most identifiably contaminated samples (66L20, 6561501, and A54-14) and clots of clinopyroxene which probably represent quartz completely reacted with magma appears in one sample (6561302). There are no xenocrysts in two samples (65L120 and 6561304) and only one xenocryst was found in a third (J54-4). These last three are our candidates for primitive basalts (i.e.—essentially uncontaminated).

Concentration Data

General. The concentrations of major elements are given in Appendix B and those of the relevant minor elements are given in Table 1. We consider that contamination can be established most reliably with petrographic criteria; however, if all the xenocrysts should be assimilated, then element concentrations and ratios are one of the two remaining criteria that can be used to establish contamination although they might also have just indicated that these basalts are differentiated relative to oceanic basalts. Also the existence of one xenocryst does not necessarily mean that the mineralogy or chemistry of the basalt has been seriously altered.

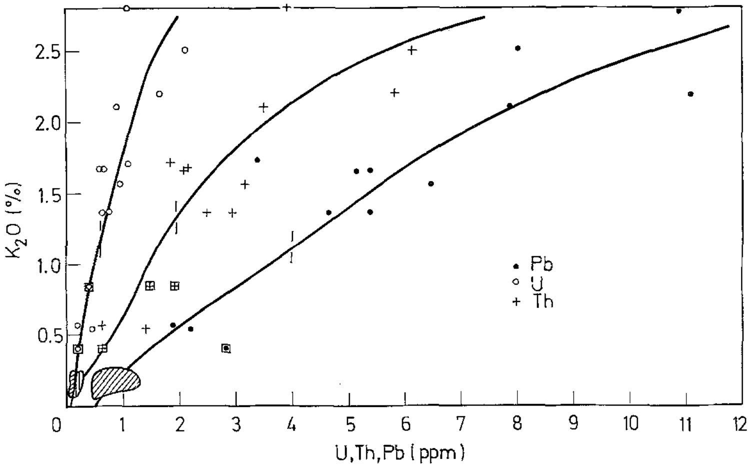

Fig. 2. Lead, uranium, and thorium contents plotted against K_2O content of primitive and obviously contaminated basalts of the Southern Rocky Mountains (U-circles, Th-crosses, Pb-dots). Trends are shown as solid lines; vertical bars show the breaking points for trace elements between primitive basalts and obviously contaminated basalts. Abyssal basalt values (Tatsumoto, 1966b) are shown by cross-hatched areas and a Hawaiian tholeiite and alkali basalt are shown as squares (Tatsumoto, 1966a)

Major Elements. The only major element that shows a correlation with the presence or absence of xenocrysts is K_2O (Fig. 2). Primitive basalts usually contain less than 1% K_2O; however, one of our candidates for a primitive basalt (65L120) has a K_2O content of 1.7%, a value greater than that of five demonstrably contaminated basalts. This basalt appears to belong to a more alkalic series than the others; potassium determinations on younger xenocryst-free basalts from the same volcano show a systematic decrease with time. Surprisingly, SiO_2 does not appear to be as reliable an indicator of contamination (and perhaps differentiation) as K_2O. The xenocryst-free sample of the Hinsdale basalts (65L120) contains at least as much SiO_2 51.3%, as do some Hinsdale basalts classified as slightly contaminated on the basis of sparse alkali plagioclase xenocrysts, 51.6 and 50.5% (66L26 and Ds29B). Surprisingly, Na_2O also does not show reliable effects with contamination. On the basis of the data available in this study, no other major element appears as reliable as K_2O in giving a trend paralleling contamination.

Table 1. *Selected trace element concentrations in basalts from the Southern Rocky Mountains*

Sample	Classification	Concentrations							
		Weight (ppm)						Atomic	
		Pb	U	Th	Rb	Sr	Rb/Sr	$\frac{^{238}\mathrm{U}}{^{204}\mathrm{Pb}}$	$\frac{^{232}\mathrm{Th}}{^{238}\mathrm{U}}$
Hinsdale formations basalts from the La Jara Reservoir region, Colorado									
66L20	very contaminated	8.04	2.14	6.15	58.1	570	0.100	16.8	3.0
		8.01	2.09	6.34					
66L26	slightly contaminated	5.4	0.76	2.96	20.7	501	0.0314	8.9	4.0
		4.66	0.65	2.46				8.8	3.9
65L120	primitive	3.40	1.11	1.85	23.2	861	0.0203	20.6	1.7
Servilleta formation of Montgomery *(1953), basalts from the Taos area, New Mexico*									
6561501	contaminated	5.39	0.63	2.08	23.9	591	0.040	7.25	3.4
6561302	contaminated	5.11	0.64	2.12	25.5	579	0.044	7.78	3.4
6561304	primitive	1.90	0.203	0.627	3.0	372	0.008	6.71	3.2
					4.3[a]	390[a]	0.011[a]		
Miscellaneous basalts from the Southern Rocky Mountains									
San Juan volcanic area, Colorado									
Jarosa Mesa (Ds29-B)[b]	slightly contaminated	7.9	0.88	3.50	36.1	808	0.0477	7.1	5.3
Race Creek (65L32)	contaminated	11.1	1.67	5.85	41.9	777	0.0539	9.5	4.7
Jemez Mountains, New Mexico									
Cerro Pelon (A54-14)[b]	contaminated	6.5	0.96	3.27	26.2	560	0.0468	9.2	3.5
Borrego Mesa[c] (J54-4)	primitive	2.2	0.45	1.40	2.4	481	0.0050	12.9	3.2
Eagle County, Colorado									
Dotsero Crater (54P152)	contaminated (?)	10.9	1.25	3.95	54.4	677	0.0804	7.3	3.3

[a] By isotope dilution.
[b] From Doe (1967).
[c] Lead, uranium, and thorium from Doe (1967).

The K_2O contents of the primitive Cenozoic basalts of the Southern Rocky Mountains (0.5—1.7%) are greater than those found in abyssal basalts [0.06 to 0.45%; Engel and Engel (1964a, b) and Gast (1965)], but two are within the range found for tholeiites and olivine tholeiites of oceanic islands such as Hawaii [0.07—0.8%; Macdonald and Katsura (1964)]. The third primitive basalt from the Southern Rocky Mountains (1.7% K_2O) is greater even than that of alkali basalts of the Hawaiian Islands [$\leqq 1.3\%$ K_2O; Macdonald and Katsura (1964)]. In the subsequent discussion, other trace element and isotopic parameters will be compared against K_2O content as a contamination index even though the concentration may also reflect differentiation. This sort of comparison is done because of the difficulty of otherwise quantifying xenocryst abundance plus xenocryst assimilation.

Minor Elements. Pb, U, and Th contents (Table 1) are plotted against K_2O in Fig. 2 in the manner described by Tatsumoto (1966b). All the xenocryst-rich basalts have Pb contents greater than 4 ppm. Th greater than 2 ppm, and U greater than 0.62 ppm. These elements seem to be very useful in recognizing basalts that are little contaminated or differentiated. Because of the low contents of K_2O (0.54%), Pb (2.2 ppm), Th (1.40 ppm) and U (0.45 ppm) in sample J54-4 from the Jemez Mountains, we consider it with the primitive basalts inspite of the presence of sparse sodic plagioclase xenocrysts. The lead content in particular apparently is very sensitive to contamination. In the Hinsdale basalts, for example, the primitive basalt (65L120) contains 3.4 ppm Pb whereas the contaminated basalts with similar contents of SiO_2 (66L26, 5L32, and Ds29-B) contain 5, 8 and 11 ppm Pb respectively. We do not know the size of the region or variety of rock types these trace element indices may apply, but our samples cover a north-south distance of approximately 300 miles.

The second test of the primitive basalt candidates is a comparison of their Pb, U, and Th contents with those of basalts from oceanic localities. The lead contents of the Southern Rocky Mountains basalts that seem to be least contaminated (1.9—3.4 ppm) are greater than those of abyssal basalts (0.49—1.3 ppm; Tatsumoto, 1966b), but are similar to those of basalts from oceanic islands such as tholeiites (1.2—3.9 ppm), a high alumina basalt (4.3 ppm), and alkali basalts (1.3—3.35 ppm), as determined by Tatsumoto (1966a, b). Therefore the candidates for primitive basalts of the Southern Rocky Mountains appear to be as primitive as are, for example, the volcanics of the Hawaiian Islands. There is no suggestion in this concentration data that the primitive basalts of the Southern Rocky Mountains are significantly contaminated with silicic crust.

There does not appear to be any smooth concentration trend for Sr concentrations in basalts from the Southern Rocky Mountains with increased contamination although Rb tends to follow K and to be greater in the xenocryst-bearing basalts. The strontium content for the Hinsdale basalts is less in the xenocryst-bearing rocks than in the primitive basalt. This is the trend expected for contamination with rocks of the upper crust. On the other hand, the Sr content of the Servilleta basalts (Montgomery, 1953) is greater in the xenocryst-bearing basalts, a trend difficult to explain except by lateral or vertical differences in strontium contents in the source rocks. The value of Rb/Sr in all the xenocryst-bearing basalts is greater than 0.035. The very low value of the ratio found for three samples in this paper is an indicator of primitive basalts. Neither Th/U nor $^{238}U/^{204}Pb$ shows reliable shifts with contamination.

Discussion of Lead Isotopes

In each set of primitive and contaminated basalts (Table 2), the contaminated basalt contains less radiogenic lead (smaller ratios) than does the companion primitive basalt. The conclusion is that crustal contamination generally results in lead isotope ratios that are less radiogenic by 2—4% in $^{206}Pb/^{204}Pb$ and roughly

Table 2. *Lead and strontium isotope ratios for basalts from the Southern Rocky Mountains*

Location and Sample No.	Classification	Lead[a]			Strontium[a]
		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{87}Sr/^{86}Sr$
Hinsdale formation, basalts from the La Jara Reservoir region, Colorado					
66L20	very contaminated	17.893	15.52	37.29	0.7051
66L109, plagioclase (light)		17.983	15.60	37.63	0.7050
66L109, plagioclase (medium)		18.267	15.58	37.91	0.7051
66L26	slightly contaminated	17.958	15.56	37.64	0.7050
65L120	primitive	18.331	15.55	37.67	0.7039
Servilleta formation of MONTGOMERY *(1953), basalts from the Taos area, New Mexico*					
6561501	contaminated	17.386	15.52	37.23	0.7043
6561302	contaminated	17.369	15.47	37.19	0.7044
6561304	primitive	18.086	15.51	37.55	0.7050
Miscellaneous basalts from the Southern Rocky Mountains					
San Juan volcanic area, Colorado					
Jarosa Mesa[b] (Ds29-B)	slightly contaminated	18.377	15.62	38.26	—
Race Creek (65L32)	contaminated	18.835	15.56	37.98	—
Jemez Mountains, New Mexico					
Cerro Pelon[c] (A54-14)	contaminated	17.78	15.50	37.60	0.7044
Borrego Mesa[c] (J54-4)	primitive	18.34	15.46	37.86	0.7047
Eagle County, Colorado					
Dotsero Crater (54P152)	contaminated (M)	17.93	15.63	38.63	0.7055[d]

[a] All lead ratios are normalized to values obtained on tantalum lot 1 filament materials in the manner described by DOE (1967); all strontium data are normalized to a value of 0.7080 for $^{87}Sr/^{86}Sr$ of the M.I.T. Eimer and Amend $SrCO_3$ reference sample.

[b] From DOE (1967).

[c] Lead isotope ratios from DOE (1967).

[d] From HEDGE and WALTHALL (1963).

1% in $^{208}Pb/^{204}Pb$. This conclusion is the same as that reached previously in less well controlled studies (DOE, 1968), but the conclusion based on tight geologic control is more rigorous inasmuch as two samples of contaminated Hindsale basalt from elsewhere in the San Juan volcanic area have the most radiogenic lead isotope ratios of any of the samples from the region.

That the upper crust is radiogenic in its present-day lead isotopic composition is generally accepted (for example, see Chow and Patterson, 1962; Patterson and Tatsumoto, 1964; Doe, 1967); therefore, contamination by upper crustal granitic rock that results in nonradiogenic lead seems unlikely. Some radiogenic lead may be lost from the granite before it is incorporated into the basalt magma (Doe, 1967), and as a result the assimilated rock may be nonradiogenic. An alternative possibility is that the assimilated material is Precambrian silicic granulite from the lower crust. Such silicic material is apparently permitted by the studies of Den Tex (1965) and Ringwood and Green (1966). An attractive hypothesis is that the lower crust may contain nonradiogenic lead at least under some regions (Patterson and Tatsumoto, 1964; Doe, 1968; Zartman, 1968) because of depletion of uranium and thorium relative to lead in Precambrian times due to granulite or eclogite facies metamorphism.

In addition sodic plagioclase was separated from the xenocryst-bearing Hinsdale basalt (66L109) which is a re-collection of basalt from the 66L20 locality. The lead in the low-density xenocryst-rich fraction of plagioclase has isotopic ratios similar to those in the whole rock, whereas the medium-density fraction, perhaps rich in phenocrysts, has a $^{206}Pb/^{204}Pb$ close to that of the primitive basalts. The $^{208}Pb/^{204}Pb$ value of the medium-density fraction is slightly more radiogenic than other samples from the Hinsdale basalt suite (Table 2). These isotopic differences between plagioclase and whole rock are definitive evidence that all the plagioclase cannot be phenocrysts of one unaltered melt. Lead isotope differences can develop only by mixing of leads of different isotopic compositions or by generating lead through decay of uranium and thorium to lead in systems containing different values of U/Pb and Th/Pb over long periods of time such as hundreds of millions of years. The medium-density plagioclase must therefore be foreign to the contaminated magma that later crystallized around it. The best interpretation seems to be that this plagioclase fraction probably contains much phenocrystic plagioclase that crystallized from the melt prior to the contamination.

Surprisingly, the medium-density plagioclase did not exchange lead with the melt to come into isotopic equilibrium. Perhaps the explanation of why this did not occur lies in the study of O'Neil and Taylor (1967) on cation and oxygen isotope exchange in feldspars. They found that it was necessary for the feldspar to undergo recrystallization (solution and redeposition) to obtain cation exchange. As the calcic plagioclase was in equilibrium with the melt, no recrystallization is expected. The similarity of the lead isotope ratios between the sodic plagioclase and the melt is probably a coincidence, inasmuch as preservation of sodic plagioclase that has undergone solution and redeposition to obtain cation exchange in a basalt melt under shallow conditions is unlikely. Probably the calcic armor on sodic plagioclase prevented recrystallization or, equally likely, in water-poor basalt perhaps no fluid phase was present to facilitate recrystallization.

The isotopic compositions of the basalts from the Southern Rocky Mountains are compared with those of oceanic basalts in Fig. 3. If we take lead content as a rough index of contamination, then the primitive basalts from the Southern Rocky Mountains are similar both in lead content and in the values of $^{206}Pb/^{204}Pb$ to those of primary basalt types (tholeiites, alkali basalts, and high alumina basalts of Hawaii and eastern Honshu, Japan) although the values of $^{208}Pb/^{204}Pb$ are distinctly

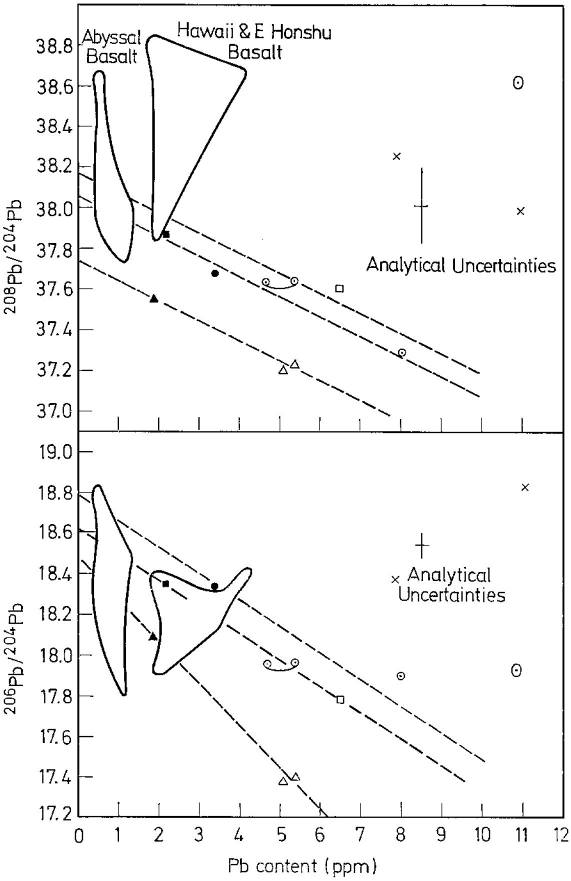

Fig. 3. Lead content plotted against ^{206}Pb/^{204}Pb at the bottom and ^{208}Pb/^{204}Pb at the top. Labeled areas are data from Tatsumoto (1966a, b) from oceanic areas as labeled, and are shown for comparison. Dashed lines are drawn to fit the data as well as possible for the three sets of data obtained from areas where uncontaminated and contaminated basalts may be related (▲, △ — Servilleta formation of Montgomery (1963), basalts, ●, ○ — Hinsdale formation, basalts, and ■, □ — basalts from the Jemez Mountains). Closed symbols are primitive basalt, open are contaminated. Older samples of contaminated basalts from the Hinsdale Formation elsewhere in the San Juan Mountains are shown by X. The basalt from Dotsero Crater is shown by ◇

lower in the basalts from the Rocky southern Mountains. This ratio difference may not be significant inasmuch as the primitive basalts of both the Southern Rocky Mountains and Hawaii are less radiogenic than would be expected from closed-system models of lead evolution for the accumulation of radiogenic lead since the earth began (^{208}Pb/^{204}Pb ~ 38.4), and both range in values of ^{208}Pb/^{204}Pb. The lead content of the basalts appears to vary proportionally with the isotopic composition (Fig. 3). We see that a projection back to a lead content of abyssal basalts results in comparable lead isotope ratios for those observed in the primitive basalts and also with those of the abyssal basalts. Thus the observed lead isotope ratios in the primitive basalts appear to give us a reasonable approximation of what the lead isotopic composition was in the magma at its source. In addition, this isotopic composition for lead in the source of primitive basalts from the Southern Rocky Mountains is not drastically different from that in either the source of abyssal basalts or in Hawaiian or eastern Honshu basalts. The important feature is that there is no reason to suspect that our primitive basalts have been more altered by crustal contamination than those of the Hawaiian Islands, for example.

Discussion of Strontium Isotope Data

The value of $^{87}Sr/^{86}Sr$ for the primitive Hinsdale basalt sample is similar to that of most basalts from the ocean basins ($^{87}Sr/^{86}Sr \leqq 0.704$). The primitive basalt from the Servilleta formation of MONTGOMERY (1953) has a value of $^{87}Sr/^{86}Sr$ of 0.705, which is somewhat greater than that of most basalts from the ocean basins. Commonly the mantle under the continents is assumed to be similar in $^{87}Sr/^{86}Sr$ to that under the ocean basins, however the data of HEDGE (1966) on the primitive basalts of the Snake River Plain ($^{87}Sr/^{86}Sr \leqq 0.705$) may be interpreted to indicate that mantle under the continents is more radiogenic in some regions than that under the ocean basins (DOE, 1968).

The contaminated samples of Hinsdale basalt are more radiogenic than is the primitive sample. This trend is similar to that found by HEDGE (1966) for the contaminated samples from the Craters of the Moon relative to the primitive basalt from Shoshone Falls on the Snake River Plain. This trend is the effect expected from Precambrian crustal contamination inasmuch as all the abundant Precambrian metamorphosed rocks in the Rocky Mountains are very radiogenic (GILETTI, 1966; MOORBATH, HURLEY, and FAIRBAIRN, 1967), but the effect is so small that it could well be due to lateral or vertical variations in the source. The contaminated basalt of the Servilleta basalt are slightly less radiogenic (approximately 0.1%) than their primitive companion (Table 2). This effect cannot be due to contamination since a mass balance calculation would require almost 100% of the strontium to come from contamination. The effects from crustal contamination seem to be small, and therefore any lateral or vertical variation in the source of the Hinsdale basalt or Servilleta basalt might obscure any contamination effect.

Lead shows more obvious isotope effects from contamination than does strontium, probably because of mass balance considerations. Lead content in upper crustal rocks is 5—10 times that in uncontaminated basalts, whereas the strontium content in the upper crust is perhaps about half that of our primitive basalts. Therefore assimilation of 10% of crustal material will change the lead isotopic composition to about halfway between the primitive and the contaminating materials, whereas the strontium would change only about 5% of the isotopic difference between these materials. As strontium in basalts apparently is buffered against crustal contamination, we prefer to interpret the small observed strontium isotope variations as due mainly to slight lateral or vertical variations in the source.

Strontium in both densities of plagioclases of sample 66L109 (Table 1) is isotopically similar to that of the whole rock in contrast to the variation in lead isotopic composition. This might be explained by differential cation exchange of lead and strontium; however, this sort of exchange seems unlikely in view of the cation exchange study of O'NEIL and TAYLOR (1967). The isotopic similarity is more likely a coincidence, because a $^{87}Sr/^{86}Sr$ of 0.705 is a reasonable value for a Precambrian plagioclase. Any mass balance consideration of accounting for the ratio differences between lead and strontium isotopes from mixing of xenocrysts with phenocrysts favors the xenocrysts as having a greater effect on the lead isotopes inasmuch as upper crustal plagioclase coexisting with K-feldspar

Appendix A. *Sample descriptions of basalts from the Southern Rocky Mountains (e = euhedral, s = subhedral, i = interstitial, equant or anhedral)*

	Phenocrysts			Xenocrysts		Groundmass							Location	
	Olivine	Clinopyroxene	Plagioclase	Sodic plagioclase	Quartz	Olivine	Clinopyroxene	Plagioclase	Cryptocrystalline or Glass	Opaques	Apatite	Vesicles	Lat. N.	Long. W
Hinsdale formation, San Juan volcanic area, southern Colorado														
Contaminated olivine basalt (66L20)	4e-s	1	←— 3i —→		2	5	10	35	20	4	1	15	37° 17′	106° 10′
Slightly contaminated basalt (66L26)	5e	—	—	—	(1 grain)	8	16	40	8	6	2	15	37° 17′	106° 11′
Primitive basalt (65L120)	5s	—	—	—	—	10	15	55	3	8	2	2	37° 4′	106° 12′
Slightly contaminated basalt (Ds29B)	25e-s	—	49e	~1	—	8	21	46	—	8	1	1	37° 58′	107° 13′
Contaminated basaltic andesite[a] (65L32)	3e	8s-i	27e	~1	—	6	9	33	5	6[a]	1	—	37° 32′	106° 37′
Servilleta formation of MONTGOMERY *(1953), Rio Grande Gorge, northern New Mexico*														
Contaminated olivine basalt (6561501)	5e	—	←— 25e-s —→		—	10	20 (augite)	35	—	5	—	—	36° 39′	106° 36′
Contaminated olivine basalt (6561302)	5e	—	←— 25e-s —→		(clinopyroxene[b] aggregates)		20 (augite	35	—	5	—	—	36° 39′	106° 36′
Primitive olivine tholeiite (6561304)	5e-s	—	—	—	—	10	25 (augite)	50	5	5	—	(diktytaxitic)	36° 39′	106° 36′
Basalts of the Jemez Mountains, northern New Mexico														
Contaminated olivine basalt (A54-14)	5e-s	—	←— 10e —→		(1 grain)	8	12	40	15	4	1	5	36° 8′	106° 24′
Primitive olivine basalt[c] (J54-4)	—	—	—	1 grain ?	—	15i	25i	50e	5	5	trace	—	36° 8′	106° 24′
Basalt at Dotsero Crater, Eagle County, Colorado														
Contaminated basalt[a] (54P152)	8e	6e-s	13e	—	(d)	—	—	—	50	—[c]	—	20	39° 39′	107° 4′

[a] About 1 percent of opaque phenocrysts for 65L32 and 3 percent in 54P152.
[b] AOKI (1967) reports quartz in his thin section.
[c] Diabasic or doleritic texture.
[d] Quartz is known from elsewhere in this flow.

Appendix B. *Whole-Rock chemical analyses*

	Hinsdale formation, basalt			Servilleta formation of Montgomery (1953), basalt			Other ages of Basalt in Hinsdale formation		Basalts in Jemez Mts.		Basalt of Dotsero Crater
	65L120[a]	66L26[a]	66L20[a]	6561304[b]	6561302[b]	6561501[b]	Ds29B	65L32	J54-4[d]	A54-14[e]	54P152[f]
SiO_2	51.3	51.6	56.8	48.57	51.55	51.51	50.5	51.7	49.02	52.79	47.6
Al_2O_3	17.1	14.4	14.3	16.88	17.53	17.47	16.6	17.3	16.12	16.96	16.0
Fe_2O_3	2.9	4.5	3.0	2.90	3.93	3.68	4.3	5.8	3.94	1.97	4.5
FeO	6.1	6.9	4.9	8.43	5.07	5.72	5.5	4.0	6.94	6.81	6.7
MgO	6.6	6.3	5.6	7.63	5.76	5.76	5.8	4.0	7.51	5.62	7.3
CaO	7.6	8.0	6.6	9.02	7.64	7.74	8.5	7.4	10.17	8.50	8.8
Na_2O	4.21	3.1	3.5	2.81	3.63	3.41	3.4	3.4	3.12	3.54	3.3
K_2O	1.7	1.3	2.4	0.56	1.67	1.67	2.1	2.2	0.54	1.56	2.8
H_2O^-	0.10	0.36	0.47	0.29	0.52	0.22	0.21	0.88	0.23	0.08	0.12
H_2O^+	0.25	0.54	0.43	0.85	0.81	0.66	0.34	0.72	0.20	0.37	0.47
TiO_2	1.6	1.8	1.3	1.50	1.61	1.49	1.7	1.4	1.59	1.22	1.6
P_2O_5	0.45	0.41	0.39	0.20	0.31	0.32	0.79	0.51	0.37	0.36	0.54
MnO	0.14	0.07	0.12	0.16	0.14	0.09	0.11	0.14	0.17	0.14	0.13
CO_2	<0.05	<0.05	0.21	—	—	—	<0.05	0.09	0.01	0.02	<0.05
Sum	100	99	100	99.80	100.17	99.74	100	100	99.93	99.94	100
Na_2O	4.22[c]	3.06[c]	3.58[c]				3.42	3.55			
K_2O	1.71[c]	1.36[c]	2.50[c]				2.02	2.35			

[a] Rapid rock analyses by Paul Elmore, H. Smith, Gillison Chloe, J. Glenn, Lowell Artis, S. D. Botts, U. S. Geological Survey, Washington, D. C.

[b] K. Aoki, analyst; Aoki (1967).

[c] Determined by flame photometer by Violet Merritt, U. S. Geological Survey, Denver, Colorado.

[d] Standard rock analysis by J. L. Theobald. Borrego Mesa, west side of lower flow, third unit from bottom. Description by Roy Bailey, U. S. Geological Survey, Washington, D. C.

[e] Standard rock analysis by L. N. Tarrant. Basalt overflows dacite north of Cerro Pelon, Baslarde. Description by Roy Bailey, U. S. Geological Survey, Washington, D. C.

[f] Rapid rock analysis by Paul Elmore, H. Smith, J. Kelsey, Gillison Chloe, Lowell Artis, and J. Glenn, U. S. Geological Survey, Washington, D. C.

certainly contains more lead than does basalt, whereas the strontium content of upper crustal granitic plagioclases is less than that in basalts.

Conclusions

1. Basalts may be found in the Southern Rocky Mountains that are as uncontaminated by silicic continental crust as are basalts from oceanic islands.
2. Contamination of basalt by old silicic crust in the Southern Rocky Mountains results in making the lead in basalt less radiogenic than its primitive parent. Strontium isotopic composition is little affected by such contamination in the Southern Rocky Mountains.
3. Plagioclase does not completely exchange its lead with the surrounding basalt melt.

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