**Uranium, Thorium, and Lead Concentrations and
Lead Isotopic Composition of Biotite
Granodiorite (Sample 9527-2b) from
LASL Drill Hole GT-2**

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LA-7923-MS
Informal Report
UC-66b
Issued: July 1979

Uranium, Thorium, and Lead Concentrations and Lead Isotopic Composition of Biotite Granodiorite (Sample 9527-2b) from LASL Drill Hole GT-2

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URANIUM, THORIUM, AND LEAD CONCENTRATIONS AND
LEAD ISOTOPIC COMPOSITION OF BIOTITE GRANODIORITE
(SAMPLE 9527-2b) FROM LASL DRILL HOLE GT-2

by

Robert E. Zartman

ABSTRACT

An investigation of the uranium (U), thorium (Th), and lead (Pb) isotopic systematics was made on the whole rock, microcline, plagioclase, biotite, sphene, zircon, epidote, and pyrite of a biotite granodiorite (core sample 9527-2b) obtained from a depth of almost 3 km in Los Alamos Scientific Laboratory's (LASL) deep drill hole GT-2. Except for quartz, magnetite, and apatite, all primary mineral phases were analyzed, as were epidote and pyrite from minute epidote-calcite-pyrite veinlets formed during a later fracture filling event. The sphene and zircon data offer strong support for an initial crystallization age of about 1500 ± 20 m.y. for the biotite granodiorite. Likewise, a model age of about 1500 m.y. is calculated for the microcline. This amount of time is also required for the whole rock to evolve essentially as a closed system from an initial lead isotopic composition similar to that of the microcline. The plagioclase and biotite, on the other hand, clearly record isotopic disturbance at some time(s) subsequent to the crystallization of the rock. The isotopic systematics of the secondary epidote and pyrite do not allow for a unique determination of the age of the fracture-filling event, but suggest a more complex history of chemical migration extending perhaps from Precambrian to Phanerozoic time.

I. INTRODUCTION

Core samples made available from deep drill holes into Precambrian basement rocks of north-central New Mexico as part of the Los Alamos Scientific Laboratory (LASL) Hot Dry Rock Geothermal Energy Development Program lend themselves to a variety of geochemical and geophysical studies. The distribution of uranium, thorium, and lead and the ensuing isotopic evolution of the lead within the mineral phases of a rock hold considerable promise for establishing geochronologic constraints on the rock's geologic history and for providing a natural tracer of chemical interactions. For example, by monitoring these elements acquired by fluids circulating through the thermal reservoir, useful information may be derived about the relative rates of destruction of specific mineral phases identifiable by their lead isotopic ratios. However, before such applications can be made, characterization of samples of the fresh core rock for comparison with fluid extracted lead is necessary. Because near-surface samples often show modern disturbance of their U-Th-Pb isotopic systematics attributable to rock dilation and penetration of ground water, a knowledge of the depth to which these surface manifestations extend has important geochemical implications for general scientific as well as project-related reasons.

The detailed U-Th-Pb isotopic characterization of even a single rock specimen involving the analysis of most of its mineral phases is a time-consuming operation. Thus, while studies involving the lead isotope determination of specific minerals, such as zircon, sphene, feldspar, etc., have become quite common, only a few terrestrial rocks have been thoroughly investigated for internal systematics among their mineral phases (see, for example Tilton et al.¹, Zartman and Tera², Haines and Zartman³). Conclusions based on this preliminary study of one biotite granodiorite core sample from the 9527-foot (2903.8-m) depth in LASL Drill Hole GT-2 must be qualified accordingly. Nevertheless,

the results obtained from this single sample, together with previously published Rb-Sr, K-Ar, and fission-track data, allow significant conclusions to be drawn regarding the igneous and metamorphic history of the terrane.

II. PREVIOUS STUDIES

This report may be considered a supplement to the published geochronologic studies of Brookins et al.⁴, who have summarized therein the results on the Precambrian rocks using the Rb-Sr, K-Ar, and fission-track methods on core samples from three LASL deep drill holes, GT-1, GT-2, and EE-1. The three holes are located on the Jemez Plateau outside the west rim of the Valles Caldera in north-central New Mexico. Precambrian basement rocks were encountered at a depth of approximately 2500 feet (760 m), beneath a cover of Paleozoic sedimentary and Cenozoic volcanic rocks. The most definitive geochronologic work has been carried out on core samples from hole GT-2, which was drilled in 1974 to a depth of 9607 feet (2928 m). Brief descriptions of the geologic setting, petrography, geochemistry, and geothermal gradient given by Brookins et al.⁴ are equally relevant to the present study and will not be repeated here.

The petrographically and chemically homogeneous biotite granodiorite (see page 4, Brookins et al.⁴), which extends from a depth of 8490 feet (2588 m) to near the bottom of the GT-2 hole, provided sample 9527-2b for this investigation. An average chemical analysis for five samples of the biotite granodiorite is given in their Table 1 (see page 12, Brookins et al.⁴). A newly determined model analysis of sample 9527-2b may be compared with those of adjacent samples, previously published by Laughlin and Eddy⁵, in Table 1 of this report.

Brookins et al.⁴ determined 16-sample whole-rock isochron age of 1290 ± 30 m.y. and a $(^{87}\text{Sr}/^{86}\text{Sr})_0$ of 0.7069 ± 0.0011 on the biotite granodiorite, but this calculation is dominated by one very high Rb/Sr sample. A mineral isochron age of 1100 ± 20 m.y. for sample 9529 of the biotite granodiorite--just 0.7 m

below the sample used in the present study--is essentially a biotite age, which the authors interpret as possibly reflecting "a local metamorphic event." Real scatter outside of analytical uncertainty exists in both the whole-rock and mineral isochrons, and one might question whether either a crystallization or metamorphic age can be accurately defined by these data. A maximum age of about 1700 m.y. for this essentially undeformed igneous rock is set by that of the metamorphic complex into which it was intruded.

A profile of biotite K-Ar apparent age vs. depth was also determined by Brookins et al.⁴ to explore the effect of increasing downhole temperature on the argon retentivity of this mineral. Only for the deepest sample, 9529, does there seem to be some lowering of age to 1260 ± 40 m.y. compared to a value of 1370 ± 30 m.y. found elsewhere throughout the hole and attributed to a Precambrian regional metamorphism. A very similar profile exists for sphene fission-track ages, with sample 9529 giving a 1050 ± 150 m.y. age compared to a 1300 to 1400 m.y. age for all shallower samples. A much more drastic reduction of apatite fission-track ages occurs whereby all samples below a depth of 6000 feet (1800 m) have effectively been reset to 0 m.y. The present bottom-hole temperature of GT-2 is 197°C, and this temperature is thought to be the maximum felt at this depth in the last 1370 m.y. (assuming biotite K-Ar and sphene fission-track "blocking" temperatures of about 200°C).

III. SAMPLE HANDLING PROCEDURES

A section of core 2 1/4 in. (5.7 cm) in diameter and 3 3/4 in. (8.5 cm) in length, designated as sample 9527-2b, was obtained from A. W. Laughlin of LASL. This specimen of biotite granodiorite was chosen as the most suitable material for an initial investigation of U-Th-Pb isotopic systematics because of its extreme freshness, freedom from fractures, and position near the base of the drill hole. The core was cut along its diameter into two halves--one

half weighing 311 g was crushed and pulverized, and the other half was saved for thin sectioning and reserve material. A split of the pulverized rock was removed for whole-rock analysis, and the remainder was sized with the -60+200 mesh fraction used to obtain mineral separates.

Standard techniques employing heavy liquids, magnetic separation, and final hand picking yielded mineral concentrates that were at least 98 percent pure except in the following cases: (1) The plagioclase (An_{32}) had a density almost equal to that of quartz, from which it could only be partially separated. A grain mount of the analyzed plagioclase concentrate showed it to contain 34 percent quartz; a corresponding correction was made to the plagioclase concentration data, assuming the quartz to be devoid of U, Th, and Pb. (2) Pyrite and zircon were both concentrated into the nonmagnetic-heavy-mineral fraction. The pyrite analysis was made by selective dissolution in HNO_3 , which appears to have left the zircon unattacked in the residue.

In order to make a material-balance calculation comparing the chemical and isotopic composition of the individual minerals with that of the total rock, a modal analysis for sample 9527-2b was determined on the basis of point counting of thin sections and on estimation of heavy-mineral abundances in the mineral separates. Because this latter method could introduce a bias if based only on the -60+200 mesh fraction, a portion of the unsized pulverized rock was used instead. The relatively fine grain size and uniform texture of the biotite granodiorite facilitated the point-counting task, and the resultant modal analysis is given in Table 1. Because the material-balance calculation is based on mass rather than volume abundances, mineral density values, as listed in Table 2, were used in conjunction with the modal analysis.

IV. ANALYTICAL RESULTS

The U-Th-Pb chemistry was carried out using a modified Krogh⁶ method of bomb digestion, after which lead was purified by bromide-form resin exchange columns. Details of reagents, bomb temperature, and length of time used to dissolve the different mineral species are summarized in Table 3. Lead concentration was determined by isotope dilution on an aliquot of the sample removed after bomb digestion, but otherwise subjected to treatment parallel to that of the isotope composition fraction. A combined U and Th tracer was added to the entire sample before digestion (except in the case of the pyrite), and uranium and thorium were separated together from the effluent from the resin column of the lead-isotope-composition fraction using the nitrate-form anion resin method of Tatsumoto⁷. Mass spectrometric analysis for (a) lead was by surface ionization from a single rhenium filament with H₃PO₄-silica gel emitter, and (b) uranium and thorium by volatilization off two rhenium side-filaments using a rhenium ionizing-filament. Blank corrections have been made to all of the analyses, although they are significant only in the cases of U and Th concentrations of the feldspars. Otherwise, the concentrations are considered accurate to ± 1 percent, and the following uncertainties are assigned to the measured lead isotope ratios:

$$^{206}\text{Pb}/^{204}\text{Pb} \pm 0.15 \text{ percent}$$

$$^{206}\text{Pb}/^{207}\text{Pb} \pm 0.10 \text{ percent}$$

$$^{206}\text{Pb}/^{208}\text{Pb} \pm 0.10 \text{ percent}$$

The lead isotopic data have been normalized to absolute values by comparison with the NBS Common lead SRM 981 ($^{206}\text{Pb}/^{204}\text{Pb} = 16.937$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.491$, $^{208}\text{Pb}/^{204}\text{Pb} = 36.721$).

The uranium, thorium, and lead concentration and lead isotopic composition of the whole rock and minerals of sample 9527-2b are tabulated in Table 4 and shown graphically in Figure 1. U-Th-Pb isotopic ages for the zircon, sphene,

and epidote are presented in Table 5 and Figure 2. Plots of $^{238}\text{U}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{232}\text{Th}/^{204}\text{Pb}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}$ for the whole rock, microcline, plagioclase, biotite, and pyrite are shown in Figures 3 and 4, respectively.

Now let us turn our attention to the material-balance calculation, details of which are given in Table 6. Although a quartz concentrate was not analyzed in this study, this mineral probably does not contribute significantly to the total U, Th, or Pb content of the rock. Furthermore, the method used to extrapolate the plagioclase concentrate analysis to a pure plagioclase end member has the effect of eliminating from the calculation whatever amount of these elements may be present in the quartz. More critical could be the consequence of omitting magnetite and, to a lesser extent, calcite and apatite from the calculation. A reconnaissance examination of these mineral concentrates by x-ray fluorescence did not detect U, Th, or Pb, but such limits still allow them to be present in amounts of several tens of parts per million. The best argument against an important contribution from any of the unanalyzed minerals is the excellent agreement between the measured and the calculated composition of the rock. From this observation it can be concluded that the U, Th, and Pb occur largely in the constituent minerals of the rock rather than in interstitial sites. About 10 percent of the lead remains unaccounted for, although there are enough uncertainties involved in the calculation to permit this slight discrepancy.

V. DISCUSSION

The radiogenic ages of the two primary accessory radioactive minerals, sphene and zircon, are in close agreement, especially if the common practice is followed of placing greatest reliance on the $^{207}\text{Pb}/^{206}\text{Pb}$ age for the somewhat discordant zircon (Table 5 and Figure 2). Together with the assumption that these original crystallizing phases of the biotite granodiorite had an

initial lead isotopic composition similar to that of the microcline, an upper concordia-intercept age of 1500 ± 20 m.y. is obtained. The internal consistency of this calculation is further strengthened by comparing the lead isotopic composition of the microcline with several recent models of common lead evolution (Stacey and Kramers⁸, Cumming and Richards⁹, Doe and Zartman¹⁰), all of which support an age of 1450 - 1550 m.y. for such a lead.

An important aspect of this study was to see how well fresh rock from this depth retained its U, Th, and Pb from the time of original crystallization until the present; i.e., how closely it approached closed-system behavior. Here we are challenged not only by the possible effects of a modern, anomalously high geothermal gradient superimposed upon incipient dilation, but also by a secondary fracture-filling event that at least caused an internal redistribution of significant amounts of the elements under investigation. It was something of a surprise, therefore, to discover the very good agreement between the calculated isotopic composition of the whole rock and the microcline at 1.5 b.y. ago. Because the correction for in situ decay in the whole rock is quite significant, the small discrepancy in the calculation can be rather firmly fixed at 3 - 5 percent--with a slight excess of ^{206}Pb and deficiency of ^{208}Pb for the whole rock. A $^{207}\text{Pb}/^{206}\text{Pb}$ secondary isochron age can be determined for the microcline and whole rock pair; however, the resultant age of 1680^{+135}_{-160} m.y. $[\Delta(^{207}\text{Pb}/^{204}\text{Pb})_{\text{WR-micr}}/\Delta(^{206}\text{Pb}/^{204}\text{Pb})_{\text{WR-micr}} = 0.1029 \pm 0.0082]$ is not very precise because of the small difference in $^{207}\text{Pb}/^{204}\text{Pb}$ ratios. As will be mentioned subsequently, several of the mineral phases give evidence of large internal disturbances in their isotopic systematics, probably related to the introduction and alteration(?) of secondary epidote-calcite-pyrite. Quite likely, some net change in the overall chemical composition of the rock took place at those times, too. Nevertheless, the close approximation to a closed system for the whole

rock--despite the fact that epidote accounts for about one-fourth the uranium and one-half the thorium--implies that either (a) the secondary minerals acquired most of their U, Th, and Pb locally from within the analyzed rock itself, or (b) the fracture-filling event occurred soon after initial crystallization.

An examination of the lead isotopic data in Table 4 reveals that only the microcline and whole rock will correct in an almost straight-forward way for in situ decay of uranium and thorium over the past 1.5 b.y. The plagioclase, biotite, and pyrite show an excess of radiogenic isotopes, and the epidote, sphene, and zircon show a deficiency of radiogenic isotopes compared to the microcline and whole rock when similarly corrected for in situ decay. The lead isotopic systematics of the latter three radioactive minerals can also be viewed as discordant U-Th-Pb ages in Table 5 and Figure 2. Qualitatively, such a pattern might be expected to arise as a result of postcrystallization loss of radiogenic daughter isotopes from the more radioactive mineral species and their gain by less radioactive species. If complete isotopic exchange was effected among all phases of the rock at some unique intermediate time in its history with no subsequent disturbance, the present-day measured isotopic compositions would plot as linear arrays on $^{238}\text{U}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{232}\text{Th}/^{204}\text{Pb}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}$ diagrams (Figures 3 and 4). The slope of these lines could then be used to determine the age when isotopic equilibrium was last attained. No such simple solution exists for the time of exchange, however, and we note in particular that the Th-Pb age of the epidote is much younger than the U-Pb ages for a wide choice of assumed initial lead isotopic compositions (Table 5). In fact, the U-Pb age suggests that the epidote formed essentially contemporaneously with the original crystallization of the rock, while the Th-Pb age requires that some disturbance of the mineral took place during or after latest Precambrian time.

Although other interpretations may be offered, the data do allow a scenario whereby the biotite granodiorite originally crystallized about 1500 m.y. ago with a normal lead isotopic composition of $^{206}\text{Pb}/^{204}\text{Pb} = 16.24$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.34$, and $^{208}\text{Pb}/^{204}\text{Pb} = 35.65$. Soon afterwards, the rock underwent brittle fracturing accompanied by secondary epidote-calcite-pyrite mineralization. These fracture fillings comprise less than 2 percent of the analyzed rock, but elsewhere in the drill core they define major shear zones, which transect the biotite granodiorite and its country rock. By assuming that the fracture filling event is not much younger than the original crystallization, the constraint that U, Th, and Pb move only locally within the analyzed rock is removed, and we may entertain the introduction of significant amounts of uranium and thorium by mineralizing fluids. Some lead isotopic heterogeneity among the mineral phases may also be established at this time as the rock and fluids interact.

The greatest redistribution of lead isotopes, however, seems to have occurred after appreciable growth of the radiogenic isotopes. Probably several periods of disturbance have affected the internal isotopic systematics of the minerals--but without further gain or loss of material from the whole rock. Low-grade metamorphism, epeirogenic movements, partial denudation, Paleozoic submergence, and Cenozoic volcanism are likely geologic agents for causing such lead exchange. At least one event affecting the epidote must be no older than late Precambrian, and the zircon is here assumed to have an essentially modern lower concordia intercept. The possibility exists that the very labile elements, U, Th, and Pb, were further disturbed during drilling and mineral separation, but it is unlikely that these operations have seriously altered the natural condition of the rock.

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TABLE 1

MODAL ANALYSIS OF SAMPLE 9527-2b COMPARED WITH THOSE
OF ADJACENT SAMPLES OF BIOTITE GRANODIORITE
FROM LASL DEEP DRILL HOLE GT-2

	<u>9527-2b</u>	<u>8578-2</u>	<u>9519-1</u>	<u>9531-1a</u>
K-feldspar	21±1	21±3	15±2	20±2
Plagioclase	37±2	34±3	38±3	37±3
(% An)	32	31+	33	36+
Quartz	23±2	29±3	25±3	23±3
Biotite	14±1	11±2	13±2	13±2
Chlorite	<u>a/</u>	<0.5	Tr	<1
Opakes	1.7	1	1	<1
Muscovite	<u>a/</u>	<0.5	<1	<0.5
Myrmekite	<u>b/</u>	1	<1	1
Calcite	0.5	<0.5	Tr	<1
Epidote	1.2	1	3±1	1
Apatite	0.05	<1	<1	<1
Sphene	1.4	2±1	2±1	2±1
Zircon	0.006	Tr	Tr	Tr
Amphibole	--	--	--	<0.5
Pyrite	0.025	--	--	--

Modal analysis of 9527-2b, this report; 8578-2, 9519-1, and 9531-1a, Laughlin and Eddy⁵. Tr <0.10%. a/ Included with biotite. b/ Included with plagioclase.

TABLE 2

MINERAL DENSITIES USED IN
MATERIAL-BALANCE CALCULATION

<u>Mineral</u>	<u>Density (g/cm³)</u>
Microcline	2.56
Plagioclase	2.65
Quartz	2.65
Biotite	3.1
Opagues	5.2
Calcite	2.7
Epidote	3.4
Apatite	3.2
Sphene	3.5
Zircon	4.6
Pyrite	5.0

TABLE 3
DETAILS OF CHEMICAL DISSOLUTION

<u>Mineral</u>	<u>Reagents</u>	<u>Bomb Temperature</u>	<u>Digestion Time</u>
Whole rock	HNO ₃ , HF	215°C	2 days
Microcline	do	150°C	overnight
Plagioclase	do	do	do
Biotite	do	do	do
Epidote	do	do	do
Sphene	HClO ₄ , HCl, HF	190°C	2 days
Zircon	HNO ₃ , HF	215°C	4 days
Pyrite	HNO ₃	50°C ^{a/}	2 hours

^{a/} Open teflon beaker.

TABLE 4
URANIUM, THORIUM, AND LEAD CONCENTRATION AND LEAD ISOTOPIC COMPOSITION OF VARIOUS MINERALS AND WHOLE ROCK FOR SAMPLE 9527-2b

Mineral	Concentration (ppm)			Measured lead isotopic composition			Corrected lead isotopic composition for 1.5 b.y. <u>in situ</u> decay		
	U	Th	Pb	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
Microcline	.02	.12	52.60	16.247	15.341	35.660	16.242	15.341	35.650
Plagioclase ^{a/}	.18	.38	8.67	16.789	15.428	36.792	16.469	15.398	36.582
Quartz	0	0	0						
Biotite	.69	1.19	4.01	20.986	15.849	39.511	17.993	15.569	37.934
Opaques	n.d.	n.d.	n.d.						
Calcite	n.d.	n.d.	n.d.						
Epidote	94.56	486.79	105.81	34.546	17.130	51.185	13.540	15.162	18.344
Apatite	n.d.	n.d.	n.d.						
Sphene	185.37	389.86	78.70	356.58	47.195	256.40	4.62	14.209	31.60
Zircon	328.78	169.42	85.47	258.30	37.581	74.259	-63.80	7.395	23.852
Pyrite	1.95	2.41	51.66	17.933	15.562	38.429	17.309	15.504	38.196
Whole rock	4.70	14.77	20.43	20.329	15.761	39.236	16.357	15.388	35.443

^{a/} Impure mineral separate containing 66 percent plagioclase and 34 percent quartz. Assuming the quartz to be devoid of U, Th, and Pb, the pure plagioclase would contain 0.27 ppm U, 0.58 ppm Th, and 13.14 ppm Pb. n.d., not determined.

TABLE 5
U-Th-Pb AGES OF ACCESSORY RADIOACTIVE MINERALS FOR SAMPLE 9527-2b

Mineral	Concentration (ppm)			Isotopic composition of lead (atom percent)				Age, in millions of years			
	U	Th	Pb	²⁰⁴ Pb	²⁰⁶ Pb	²⁰⁷ Pb	²⁰⁸ Pb	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁸ Pb/ ²³² Th
Sphene ^{a/}	185.4	389.9	78.70	0.1512	53.93	7.138	38.78	1456±15	1474±20	1500±25	1474±15
Zircon ^{a/}	328.8	169.4	85.47	0.2694	69.60	10.13	20.01	1159±10	1271±20	1465±30	1159±10
Epidote ^{a/}	94.6	486.8	105.8	0.9628	33.26	16.49	49.28	1326±15	1428±75	1583±220	724±10
^{b/}								1255±15	1357±70	1520±210	607±10
^{c/}								1214±15	1329±70	1518±210	596±10

Constants: $^{238}\text{U} = 1.55125 \times 10^{-10} \text{ yr}^{-1}$; $^{235}\text{U} = 9.8485 \times 10^{-10} \text{ yr}^{-1}$; $^{232}\text{Th} = 4.9475 \times 10^{-11} \text{ yr}^{-1}$; $^{238}\text{U}/^{235}\text{U} = 127.88$. ^{a/}Isotopic composition of initial lead assumed to be that of microcline corrected for 1.5-b.y. in situ decay. ^{b/}Isotopic composition of initial lead assumed to be that of pyrite corrected for 1.5-b.y. in situ decay. ^{c/}Isotopic composition of initial lead assumed to be that of pyrite measured today.

TABLE 6
MATERIAL-BALANCE CALCULATION FOR SAMPLE 9527-2b

Mineral	Concentration (C_i) ppm			Weight fraction (f_i)	Calculated contribution to whole rock ($C_i \times f_i$)		
	U	Th	Pb		U	Th	Pb
Microcline	.02	.12	52.60	0.19503	.0039	.0234	10.2586
Plagioclase	.27	.58	13.14	.35571	.0960	.2063	4.6740
Quartz	0	0	0	.22112	.0000	.0000	.0000
Biotite	.69	1.19	4.01	.15745	.1086	.1874	.6314
Opauques	n.d.	n.d.	n.d.	.03207			
Calcite	n.d.	n.d.	n.d.	.00490			
Epidote	94.56	486.79	105.81	.01480	1.3995	7.2045	1.5660
Apatite	n.d.	n.d.	n.d.	.00058			
Sphene	185.37	389.86	78.70	.01778	3.2959	6.9317	1.3993
Zircon	328.78	169.42	85.47	.000102	.0335	.0173	.0087
Pyrite	1.95	2.41	51.66	.000454	.0009	.0011	.0235
Whole rock	4.70	14.77	20.43	.999996	4.9383	14.5816	18.5615

$f_i = v_i \times \rho_i / \sum v_i \times \rho_i$, where v_i is the modal (volume) abundance and ρ_i is the density of mineral species i .
n.d., not determined.

Fig. 1.

$^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ and ^{206}Pb vs. $^{208}\text{Pb}/^{204}\text{Pb}$ diagram of the whole rock and mineral lead isotopic compositions of sample 9527-2b. Microcline (Mi), plagioclase (Pl), pyrite (Py), whole rock (WR), biotite (Bi), epidote (Ep), zircon (Zi), and sphene (Sp).

Fig. 2.

Concordia diagram for zircon (Zi), epidote (Ep), and sphene (Sp) of sample 9527-2b. Ep(a), Ep(b), and Ep(c) refer to the three assumed initial lead corrections for epidote given in Table 5.

Fig. 3.

$^{238}\text{U}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ diagram of the microcline (Mi), plagioclase (Pl), pyrite (Py), biotite (Bi), and whole rock (WR) of sample 9527-2b. Arrows pointing to sphene (Sp), epidote (Ep), and zircon (Zi) emanate from the microcline.

Fig. 4.

$^{232}\text{Th}/^{204}\text{Pb}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}$ diagram of the microcline (Mi), plagioclase (Pl), pyrite (Py), biotite (Bi), and whole rock (WR) of sample 9527-b. Arrows pointing to sphene (Sp), zircon (Zi), and epidote (Ep) emanate from the microcline.