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انجمن بلورشناسی و کانی شناسی ایران

آنالیز ایزوتوپی کانی‌ها جهت تعیین منشاء سنگ‌های آتشفشانی دگرسان شده: مثالی از لامپروئیت‌های لوسیت هیلز

حسن میرنژاد[۱]، کیت بل[۲]

۱- سازمان زمین شناسی، اتاوا، آنتاریو، کانادا .
۲- مرکز علوم زمین، دانشگاه کارلتون، اتاوا، آنتاریو، کانادا.
پست الکترونیکی: hmirneja@nrcan.gc.ca

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چکیده: مطالعه لامپروئیت‌های منطقه لوسیت هیلز، وایومینگ، نشان می‌دهد که ترکیب ایزوتوپی تعدادی از نمونه‌ها به دلیل دگرسانی و یا حضور ناخالصی‌های کربناته ثانویه در سنگ کل تغییر یافته‌اند. شستشوی نمونه‌ها توسط اسید نشان می‌دهد که اگرچه فلوگوپیت لامپروئیت‌ها تحت تأثیر فرآیندهای ثانویه واقع نشده‌اند، مادوپیتیک ترانریشنال واقع در منطقه کوه‌های میدل تیبل و یک مدوپیتیک لامپروئیت در منطقه پیلوت بیوت به مقدار زیادی تحت تأثیر فرآیندهای فوق قرار گرفته‌اند. مقایسه ترکیب ایزوتوپی Sr و Nd در انکلاوهای رسوبی و لامپروئیت‌ها نیز به تشخیص نمونه‌های تحت تأثیر قرار گرفته کمک می‌نماید. براساس این مشاهدات، کانی‌های تعدادی از نمونه‌ها جدا شده و جهت اندازه‌گیری ترکیب ایزوتوپی Sr و Nd آنالیز گردیدند. آنالیز کلینوپیروکسن، آپاتیت و پروسکیت لامپروئیت‌های لوسیت هیلز مطمئن‌ترین روش برای اندازه‌گیری ایزوتوپی نمونه‌های تحت تأثیر قرار گرفته می‌باشد. ترکیب ایزوتوپی کانی‌ها نمایانگر آن است که نمونه‌های سنگ کل منطقه کوه‌های میدل تیبل معرف مذاب والد نبوده و نیز شایسته است که مادوپیتیک ترانزیشنال لامپروئیت‌ها تحت عنوان مادوپیتیک لامپروئیت تقسیم‌بندی شوند. تغییرات نسبت‌های ایزوتوپی در دیاگرام Nd – Sr نشانگر آن است که مادوپیتیک لامپروئیت‌ها از منبع گوشته‌ای منشاء گرفته‌اند که از نظر ژئو شیمیایی با منبع گوشته‌ای فلوگوپیت لامپروئیت متفاوت هستند.

واژه‌های کلیدی: *شستشو دهنده‌ها، لامپروئیت‌ها، لوسیت هیلز، کانی‌های جدا شده، وایومینگ*

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Isotopic analysis of mineral phases to unravel the origin of altered volcanic rocks: an example from the Leucite Hills lamproites

Hassan Mirnejad[1] **, Keith Bell**[2]

1- Geological Survey of Canada,601Booth Street,Ottawa,Ontario,CanadaK1A 0E8
2- Ottawa-Carleton Geoscience Centre, Department of Earth Sciences, Carleton University, Ottawa, Ontario, Canada K1S 5B6
Email: hmirneja@nrcan.gc.ca

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Abstract: Study of lamproites from Leucite Hills, Wyoming, indicates that the isotopic compositions of some specimens have been modified due to the alteration and/or the presence of secondary carbonate impurities within the whole rocks. Leachate test shows that while phlogopite lamproites are not affected by secondary processes, the transitional madupitic lamproites from Middle Table Mountain and one madupitic lamproite from Pilot Butte localities are most affected by the mentioned processes. Comparing the Sr and Nd isotopic compositions of sedimentary enclaves with those of lamproites also pinpoints affected samples. Based on such observation, mineral grains from a number of samples were separated and analysed for Sr and Nd isotopic compositions. The analysis of clinopyroxene, apatite and perovskite from the Leucite Hills lamproites provides the most reliable mean for determining the isotopic composition of the affected samples. It also shows that the the whole rock samples from Middle Table Mountain are not representative of their parental melts and that the transitional madupitic lamproites should be classified as madupitic lamproites. Variation of isotopic ratios on Nd vs Sr isotopic diagram suggests that the madupitic lamproites have originated from a mantle source that was geochemically different from that of the phlogopite lamproites.

Keywords: *leachates, lamproites, Leucite Hills, mineral separates, Wyoming*

1. Introduction

Obtaining fresh samples is the foremost important criteria when it comes to studying the geochemistry of igneous rocks. However, during the course of such studies, we may encounter outcrops which are either altered or contain sedimentary veins and thus difficult or impossible to acquire representative samples. It seems plausible that prior to studying the major element, trace element and isotopic composition of igneous rocks from these outcrop, an evaluation is performed on the effect of alteration and possible crustal contamination on the geochemistry of the analyzed samples. The effects of crustal contamination and secondary carbonate alteration are best evaluated by: (1) analyzing the leachate, residual and unleached lamproite samples for their isotopic ratios, (2) comparing the major and trace element composition and isotopic ratios of igneous rocks and their crustal enclaves. If it turns out that the studies samples have been affected by the alteration and/or the presence of sedimentary veins, then the chemical composition of magma that crystallized the igneous rocks may be estimated by measuring the isotopic ratios of separated mineral phases.

An example of the mentioned approach is presented here by studying lamproite samples from Leucite Hills, a number of which contain carbonate veins and crustal enclaves. Such veins and enclaves are usually impossible to avoid during sample preparation and thus the isotopic composition of the mineral separates from the Leucite Hills lamproites is expected to more accurately represent the initial isotopic ratios of the original magma. Because certain minerals are less susceptible to alteration than the whole rocks, the isotopic composition of these mineral phases can help place some constraints on the initial isotopic compositions of the lamproite magma.

2. Geology

The Leucite Hills lamproites are located at 41°47´N, 109°00´W, northeast of Rock Springs in Wyoming, USA (Fig. 1). They cut through Upper Cretaceous to Eocene clastic sedimentary rocks and overly a thick cratonic basement known as the Wyoming Archean Province. The Leucite Hills lamproites are composed of 22 volcanic occurrences that range in age from 0.8 to 3.1 Ma [1]. Lamproites are oriented NW-SE and parallel some of the structural features such as the Farson Lineament and a Maastrichtian thrust fault, produced during the Laramide Orogeny [2].

The Leucite Hills lamproites crop out as small groups of volcanic cones, lava flows, plugs and dykes. Highly vesicular scoria and cinders are the dominant materials that make up the tephra cones, whereas flow units and some pyroclastic deposits commonly form composite cones. From field observations, it appears that pyroclastics either post-dated or formed simultaneously with the lava flows. The lava flows vary considerably in thickness from <1 m on the sides of the cones to > 20 m downlope.

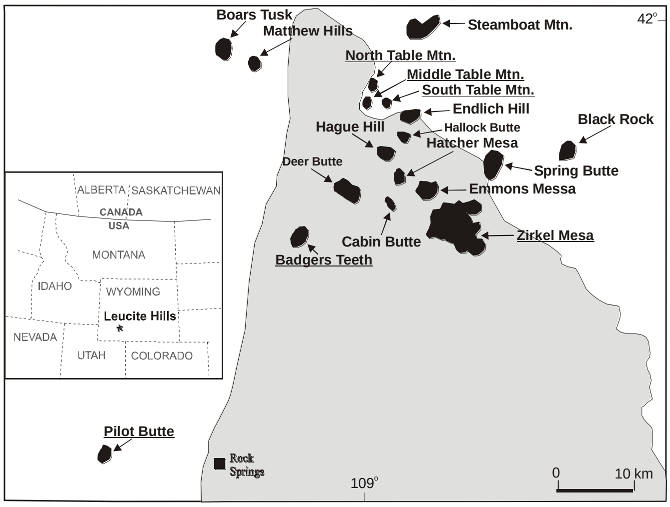

Fig. 1 The Leucite Hills lamproites (0.8 - 3.1 Ma) are located north of Rock Springs in Wyoming, USA. The localities of the samples analyzed in this study are underlined.

3. Petrography

The Leucite Hills lamproites consist mainly of a combination of phlogopite, diopside, sanidine, leucite, apatite, perovskite and minor K-rich richterite [$Na(Na,Ca)\ Mg_5Si_8O_{22}(OH)_2$], wadeite [$K_2ZrSi_3O_9$], priderite [$(K,Ba,Cs)_{1-2}(Fe,Cr,Al,V,Ce)_{1-2}(Ti,Nb)_{7-6}O_{16}$] and sherbakovite [$(BaK)(K,Na)Na(Ti,Nb,Zr,Fe)_2Si_4O_{14}$]. Of these minerals, phlogopite, clinopyroxene, and apatite can occur as either phenocrysts and microphenocrysts or groundmass crystals, whereas the remainders of the minerals usually crystallize as groundmass phases. Olivine is also found in lamproites, but its occurrence is normally limited to large macrocrysts which have been interpreted as xenocrysts [3], and phenocrysts [4].

Based on the old terminology, lamproites from the Leucite Hills are classified as wyomingites, orendites and madupites [5]. Wyomingite contains phlogopite and diopside phenocrysts/microphenocrysts residing in a groundmass of leucite, clinopyroxene, apatite and glass. Orendite has the same mineralogy as wyomingite but sanidine, in addition to leucite, is found in the groundmass. Madupite is characterized by a distinctive abundant phenocryst/microphenocryst assemblage of diopside and poikilitic phlogopite set in a groundmass of diopside, apatite and glass. Perovskite is normally more abundant in madupite than wyomingite and orendite.

Because lamproites from different parts of the world exhibit different and distinct mineralogies and textures, a number of diverse names have been used to classify them. To avoid the use of unusual and complicated names, the old terminology of lamproites has been revised by [6, 7, 8, 9] and a straightforward approach to the classification proposed. These authors still use the term lamproite and the essential mineral phases are used as a modifying prefix, in order of increasing abundance, to describe the modal mineralogy of the lamproites. As such, the wyomingites and orendites are termed diopside leucite phlogopite lamproites and diopside sanidine phlogopite lamproites respectively. [7] also proposes that the term madupites be replaced with the term madupitic lamproites to indicate its textural difference from the other types of lamproites. [3] suggest that those lamproites containing inclusion-free phlogopite phenocrysts mantled by poikilitic phlogopite be named transitional madupitic lamproites.

The terminologies recommended by [6, 7, 8, 9] follow a logical approach, prevent a listing of complicated and unnecessary locality names, and at the same time clearly indicate the major mineral constituents of the lamproites. Thus, the names proposed by these authors are used here to classify the three main lamproite types in the Leucite Hills. It should be noted that the diopside leucite phlogopite lamproite and diopside sanidine phlogopite lamproite from the Leucite Hills are simply called phlogopite lamproites to prevent long and repetitive usage of names. Moreover, these two lamproites are genetically related and no outstanding differences are observed in their chemical and isotopic compositions. Table 1 outlines the mineralogy of the different types of lamproite in Leucite Hills and the locality where each lamproite type can be found.

Table 1 Minerals commonly found in the Leucite Hills lamproites, with increase in abundance from left to right. The locality for each lamproite type is also given.

Rock Type (Old Terminology)	Orendite	Wyomingite
Rock Type (Revised Terminology)	diopside sanidine leucite phlogopite lamproite	diopside leucite phlogopite lamproite
Principal Minerals	Di - Sa- (Lct) - Phl	Di - Lct - Phl
Accessory Minerals	Rct - Prd - Wad - Ap	Rct - Prd - Wad - Ap
Locality	North Table Mountain South Table Mountain Zirkel Mesa	Deer Butte Hatcher Mesa Zirkel Mesa

Rock Type (Old Terminalogy)	Madupite	Transitional madupite
Rock Type (Revised Terminalogy)	madupitic lamproite	transitional madupitic lamproite
Principal Minerals	Phl - Di	Phl - Lct -Di
Accessory Minerals	Rct - Prd - Wad - Prv	Rct - Prd - Wad - Prv
Locality	Pilot Butte	Middle Table Mountain Badgers Teeth

Abbreviations after [10]: Ap: apatite, Di: diopside,Phl: phlogopite, Prd: priderite, Prv: perovskite, Rct: richterite, Sa: sanidine, Wad: wadeite, Lct: leucite.

4. Method of Study

4.1 Thermal Ionization Mass Spectrometry

Radiogenic isotopic analyses were performed using a Finnigan-MAT 261 multicollector solid source mass spectrometer at Carleton University. The mass spectrometer is a multi-collector machine and operates in static mode for Sr and Nd.

Samples are loaded on either Ta or Re filaments. A standard is run prior to running the other 12 samples on the magazine. Based on numerous runs from September 1992 to February 2000, the following average values have been obtained for standards: NBS-987 $^{87}Sr/^{86}Sr = 0.710251 \pm 0.00003$, La Jolla $^{143}Nd/^{144}Nd = 0.511870 \pm 0.00003$. Uncertainties are given at the 2δ level.

Measured Sr and Nd isotopic ratios for the unspiked samples were corrected for fractionation to a $^{88}Sr/^{86}Sr = 8.3752$ and $^{146}Nd/^{144}Nd = 0.7219$. Sr and Nd isotopic ratios exceeding ± 1% of the fractionation correction values (i.e., 8.291 and 8.458 for $^{88}Sr/^{86}Sr$ and 0.7147 to 0.7291 for $^{146}Nd/^{144}Nd$) were considered as unacceptable.

4.2 Sample Digestion

Samples were digested on hot plate for 24 hours in ultrapure HF and HNO_3 using a ratio of 2:5. The solutions were evaporated to dryness and then five ml 6M HCl was added to the samples. After digestion, the samples were evaporated to near dryness and were added 2 ml of 2.5M HCl. The solution was centrifuged in a centrifuge tube for 10 minutes prior to Rb, Sr and REE column separation. To prevent contamination and high blanks, unspiked samples were put through the columns prior to the spiked samples.

5. Leaching Test

Leaching experiments have already been shown to be important in detecting the presence of crustal components in some North American kimberlites [1]. In contrast to kimberlites that are CO_2-rich, lamproites are normally H_2O-rich, and do not contain primary carbonate phases. Hence, any high CO_2 content in the lamproites is probably related to secondary alteration.

A selected number of whole rock lamproites from the Leucite Hills with the possible presence of secondary alteration and/or interaction with crustal enclaves, were leached with 1.5 molar HCl to remove any carbonate minerals. Leachates, residual materials and whole rocks were analyzed for Sr and Nd isotopic ratios. Table 2 compares the isotopic compositions of the whole rock, leachate and residual portions.

Table 2 The Sr and Nd isotopic compositions of the leachates (lcht), residual (res) and the whole rock (wr) portions of the analyzed lamproites from the Leucite Hills.

Rock Type	Sample	^{87}Sr/^{86}Sr	^{143}Nd/^{144}Nd
Trans Madp Lamp	110BGT wr	0.70545	0.51203
Trans Madp Lamp	110BGT-lcht	0.70545	0.51201
Trans Madp Lamp	110BGT- res	0.70539	0.51200
Madp Lamp	133 PLB wr	0.70549	0.51210
Madp Lamp	133 PLB-lcht	0.70550	0.51204
Madp Lamp	133 PLB-res	0.70546	0.51211
Madp Lamp	137 PLB wr	0.70550	0.51205
Madp Lamp	137 PLB-lcht	0.70562	0.51205
Madp Lamp	137 PLB-res	0.70548	0.51202
Trans Madp Lamp	147MTM wr	0.70637	0.51209
Trans Madp Lamp	147MTM-lcht	0.70694	0.51208
Trans Madp Lamp	147MTM-res	0.70606	0.51207
Trans Madp Lamp	149MTM wr	0.705685	0.512056
Trans Madp Lamp	149 MTM-lcht	0.70583	0.512057
Trans Madp Lamp	149 MTM-res	0.70559	0.512056
Phg Lamp	141NTM wr	0.70591	0.51188
Phg Lamp	141NTM-lcht	0.70596	0.51187
Phg Lamp	141NTM-res	0.70595	0.51186
Ol Phg Lamp	151STM wr	0.70592	0.51181
Ol Phg Lamp	151STM-lcht	0.70598	0.51181
Ol Phg Lamp	151STM-res	0.70595	0.51180
Phg Lamp	119ZM wr	0.70574	0.51187
Phg Lamp	119ZM-lcht	0.70572	0.51187
Phg Lamp	119ZM-res	0.70575	0.51191

Bold italic numbers represent data from samples that show isotopic ratio differences between leachate, residual and unleached portions. Trans Madp Lamp = transitional madupitic lamproites, Madp Lamp = madupitic lamproites, Phg Lamp = phlotopite lamproites, Ol Phg Lamp = olivine-bearing phlogopite lamproites.

It can be seen that the Nd isotopic ratios of the whole rock lamproites are similar to the leachates for all runs. This means that any secondary carbonate alteration has not affected the Nd isotopic composition of the lamproites. On the other hand, it appears that the Sr isotopic ratios from Middle Table Mountain show differences among the whole rock, leachate and residual portions (Fig. 2). For example, the $^{87}Sr/^{86}Sr$ ratio of the leachate from sample 147MTM is 0.70694 compared with values of 0.70636 and 0.70606 in the unleached and residual samples, respectively. Because leachate portions contain HCl-soluble fractions such as carbonate, the isotopic ratios of the residual parts should normally be closer to the true isotopic composition of the fresh lamproites. Overall, the leaching tests show that the Sr isotopic compositions of lamproites from Middle Table Mountain and 137PLB have been affected by secondary carbonate alteration.

6. Chemical composition of the sedimentary enclaves

Five sedimentary enclaves were analyzed for their Sr and Nd isotopic ratios and abundances (Tables 3). It is not intended here to examine the role of assimilation in the petrogenesis of lamproites. However, a brief discussion of these data may help identify those samples whose isotopic compositions have been changed by crustal assimilation and/or the physical presence of the sedimentary enclaves. On a $^{87}Sr/^{86}Sr$ versus Sr concentration diagram (Fig. 3), the data from sample 147MTM, a transitional madupitic lamproite which contains sedimentary enclaves, plot closest to the sedimentary enclaves suggesting contamination.

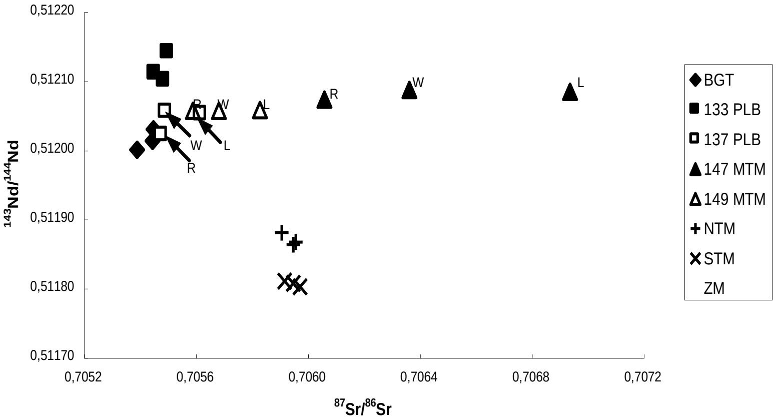

Fig. 2 Diagram showing the Sr and Nd isotopic variations among the leachate (L), residual (R) and unleached (W) samples from the Leucite Hills lamproites. Samples showing isotoipc variations outside the analytical uncertainity are labled. Badgers Teeth (BGT), Pilot Butte (PLB), Middel
Table Mountain (MTM), North Table Mountain(NTM), South Table Mountain (STM), Zirkel Messa (ZM).

Table 3 The Sr and Nd isotopic composition and concentration of sedimentary enclaves (ecv) from the Leucite Hills lamproites.

Sample	^{87}Sr/^{86}Sr	^{143}Nd/^{144}Nd	Sr	Nd
106BT-ecv	0.707861	0.511809	1871	40
114BGT-ecv	0.706855	0.512161	3253	120
133PLB-ecv	0.706396	0.512003	2330	25
137PLB-ecv	0.705755	0.512033	2982	112
140PLB-ecv	0.705694	0.512073	3182	168

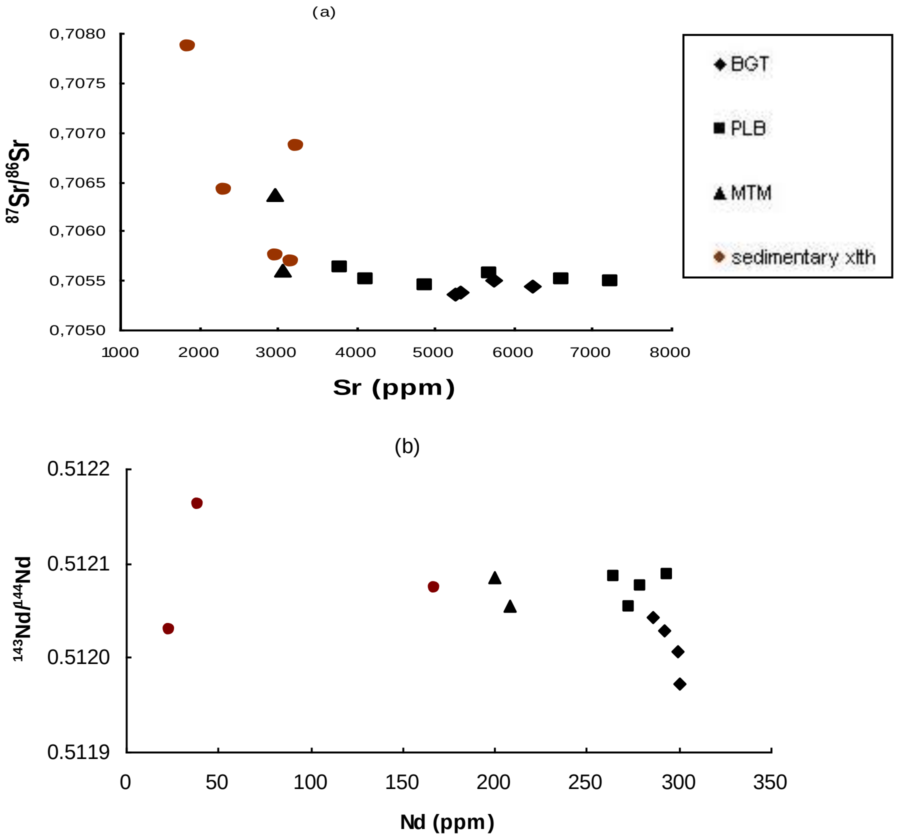

Fig. 3 (a) ^{87}Sr/^{8}Sr versus Sr, and (b) ^{143}Nd/^{144}Nd versus Nd for the sedimentary xenoliths and lamproites from the Leucite Hills. Abbreviations as in Fig. 2.

It is also clear from Figure 3 that sedimentary materials have been influential in changing the isotopic composition of sample 137PLB. These observations reveal that the chemical composition of a number of lamproites such as the transitional madupitic lamproites from Middle Table Mountain (147MTM and 149MTM) and one madupitic lamproite from Pilot Butte (137PLB) have been changed due to the presence of and/or reaction with sedimentary enclaves.

7. Mineral Separation

Whole rock specimens were trimmed and then broken into small pieces using a hydraulic jack. The broken pieces were crushed manually into powder with a steel crusher. Using plastic sieves, the powder was sieved into three sizes: >250 µm, 250-149 µm, <149 µm. The sieves were cleaned with compressed air, distilled water and ethanol between each sample. The 250-149 µm fraction was washed with distilled water in a plastic petri-dish and dried under a heating lamp. A hand magnet wrapped in a Kimwipe tissue was used to remove the strong magnetic minerals. Heavy liquids were then used to separate the minerals on the basis of their specific gravity. In methylene iodide (d = 3.29), perovskite (d = 4.03) settled whereas apatite (d = 3.1), clinopyroxene (d = 3.2) and other light minerals floated. In bromoform (d = 2.87), clinopyroxene and apatite settled whereas less dense minerals floated. Two fractions, one of perovskite and the other of clinopyroxene - apatite were rinsed with acetone and dried under a heating lamp. The mineral fractions were further purified using a Frantz isodynamic separator. The final mineral fractions were obtained by hand-picking under a binocular microscope.

The mineral phases were then placed in an ultrasonic bath, and vibrated for 10 to 20 minutes, which abraded the mineral grains and removed any attached particles. The abraded grains were washed in ethanol and nanopure water and were then leached with diluted HCL. Because the concentration of Sr and Nd had already been determined by LAM-ICP-MS, it was possible to estimate the quantity of minerals required for isotopic analysis. This was also based on the assumption that for Sr and Nd analysis, a minimum of 1 µg Sr and 500 ηg Nd were needed to analyze a sample on the mass spectrometer.

The process of digesting the minerals is similar to that for the whole rock samples and has been described in section 4.1. The isotopic composition of the mineral separates from the Leucite Hills lamproites is expected to more accurately represent the initial isotopic ratios of the magma. Because certain minerals are less susceptible to alteration than the whole rocks, the isotopic composition of the mineral phases can help place some constraints on the initial isotopic compositions of the lamproite magma. For example, the studies of isotopic composition of the perovskite grains from the eastern

North America kimberlites [12] shows that the Sr and Nd isotopic ratios of the perovskites are less radiogenic than the whole rock values.

In an attempt to evaluate the effect of alteration and crustal contamination on the isotopic compositions of the lamproites, separated mineral phases (i.e., apatite, diopside and perovskite) from Badgers Teeth, Pilot Butte and Middle Table Mountain were analyzed for their Sr and Nd isotopic ratios (Table 4). Because apatite, diopside and perovskite are the major carriers of Sr and Nd in lamproites, these minerals provide a unique opportunity to look at the combined Sr and Nd isotopic compositions of mineral phases from the same rock. The approach was restricted only to the madupitic and transitional madupitic lamproites and was not extended to the phlogopite lamproites due to the rarity of favorable minerals (i.e., apatite, diopside and perovskite) and the very small size of the mineral grains. In addition, analysis of the sedimentary enclaves as well as leaching test proved that secondary processes had not affected the traits of phlogopite lamproites.

Table 4 The isotopic composition of whole rock and separated minerals from the madupiticlamproites, Leucite Hills.

Sample	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$
112 BGT wr	0.705380	0.511972
112 ap	0.705309	0.511974
112 cpx	0.705323	0.511968
113 BGT wr	0.705343	0.512027
113 ap	0.705296	0.511982
133 PLB wr	0.705455	0.512100
133 cpx	0.705463	0.512071
135 PLB wr	0.705511	0.512085
135 cpx	0.705452	0.512044
136 PLB wr	0.705450	0.512088
136 cpx	0.705463	0.512062
147 MTM wr	0.70637	0.51209
147 cpx	0.705529	0.512067
149 MTM wr	0.705685	0.512056
149 cpx	0.705514	0.512055
149 pv	0.705501	0.512050

The results of Sr and Nd isotopic analysis of separated minerals are given in Table 4. The $^{87}Sr/^{86}Sr$ ratios show that the Pilot Butte (excluding sample 137PLB) and Badgers Teeth transitional madupitic/madupitic lamproites are in isotopic equilibrium with their mineral phases, but in the case of the Middle Table Mountain lamproite the isotopic ratios for the diopside and perovskite are different from those of the whole rock (Table 4). The leaching test has previously shown that the Sr isotopic composition of the Middle Table Mountain lamproites should indeed be lower than that of the whole rock. It is interesting to note that even though the whole rock $^{87}Sr/^{86}Sr$ ratio (0.706062) for sample 147MTM is different from that of sample 149MTM (0.705685), the Sr isotopic ratio is identical for the mineral separates from these two samples (0.70551). Assuming the mineral grains are in isotopic equilibrium with the whole rocks, the Sr isotopic ratio of the mineral separates are thus considered to be the true isotopic composition of the transitional madupitic lamproites from Middle Table Mountain. The Nd isotopic ratios show no substantial differences between the whole rock and the mineral separates from the Leucite Hills transitional madupitic/madupitic lamproites thus suggesting that the sedimentary enclaves and secondary alteration processes have had no effect on the Nd isotopic compositions of the madupitic lamproites.

Consistent with the leaching test and the chemical analysis of the sedimentary enclaves, the isotopic analysis of individual grains from the Leucite Hills lamproites shows that the Sr isotopic composition of the whole rock samples from Middle Table Mountain is not representative of the parental melt. It appears that the isotopic composition of the mineral grains more accurately represent the isotopic composition of the lamproitic melt from which the lamproites from the Middle Table Mountain crystallized. Thus, a preference is given to the isotopic composition of the mineral grains if isotopic data from both the whole rock and mineral separates are available.

8. Sr and Nd Isotopic Composition

The Sr and Nd isotopic ratios of the whole rock lamproites from this study are listed in Table 5 and plotted on Fig. 4. Only data from those samples that are not considered contaminated or altered have been reported. In addition, in cases where the isotopic composition of the whole rock and mineral separates were different, those of the minerals were used for the isotopic interpretations.

The Nd-Sr isotopic plot (Fig. 4) shows that the madupitic and transitional madupitic lamproites have higher $^{143}Nd/^{144}Nd$ ratios (0.51203 - 0.51211) than the phlogopite lamproites (0.51178 - 0.51194). The $^{143}Nd/^{144}Nd$ in the olivine-bearing phlogopite lamproites vary from 0.51178 to 0.51183. The $^{87}Sr/^{86}Sr$ ratios also indicate differences between the two groups. Ratios vary from 0.70534 - 0.70563 for the madupitic and transitional madupitic lamproites to 0.70566 - 0.70606 for the phlogopite lamproites. The Sr isotopic ratios of the olivine-bearing phlogopite lamproites are comparable to those of the phlogopite lamproites and range from 0.70584 to 0.70608.

Table 5 The Sr and Nd isotopic composition of the whole rock unaltered and uncontaminated Leucite Hills lamproites.

Rock type	Sample	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
madp lamp	110BGT	0.705451	0.512029	17.457	15.484	37.272
madp lamp	112BGT	0.705380	0.511972	17.446	15.484	37.463
madp lamp	113BGT	0.705343	0.512027	17.436	15.473	37.424
madp lamp	114BGT	0.705512	0.512043	17.442	15.481	37.459
madp lamp	116BGT	0.705370	0.512007	17.444	15.484	37.455
madp lamp	147MTM	0.705514	0.512086	17.534	15.491	37.501
madp lamp	149MTM	0.705512	0.512055	17.535	15.496	37.512
madp lamp	133PLB	0.705488	0.512100	17.556	15.508	37.489
madp lamp	135PLB	0.705511	0.512085	17.542	15.489	37.480
madp lamp	136PLB	0.70545	0.512088	17.547	15.496	37.517
madp lamp	138PLB	0.705561	0.512112	17.563	15.490	37.485
madp lamp	140PLB	0.705631	0.512075	17.583	15.504	37.523
phg lamp	119ZM	0.705741	0.511872	17.227	15.464	37.318
phg lamp	120ZM	0.705659	0.511908	17.182	15.462	37.258
phg lamp	122ZM	0.705683	0.511940	17.220	15.467	37.320
phg lamp	141NTM	0.705909	0.511879	17.273	15.482	37.280
phg lamp	143NTM	0.706025	0.511862	17.281	15.482	37.278
phg lamp	144NTM	0.70606	0.511888	17.282	15.478	37.203
phg lamp	146NTM	0.70603	0.511871	17.239	15.470	37.239
phg lamp	150STM	0.705852	0.511782	17.227	15.470	37.159
phg lamp	151STM	0.705843	0.511830	17.254	15.477	37.188
phg lamp	152STM	0.706079	0.511781	17.250	15.460	37.130
phg lamp	153STM	0.70592	0.511809	17.253	15.459	37.170
phg lamp	154STM	0.705951	0.511806	17.247	15.466	37.158

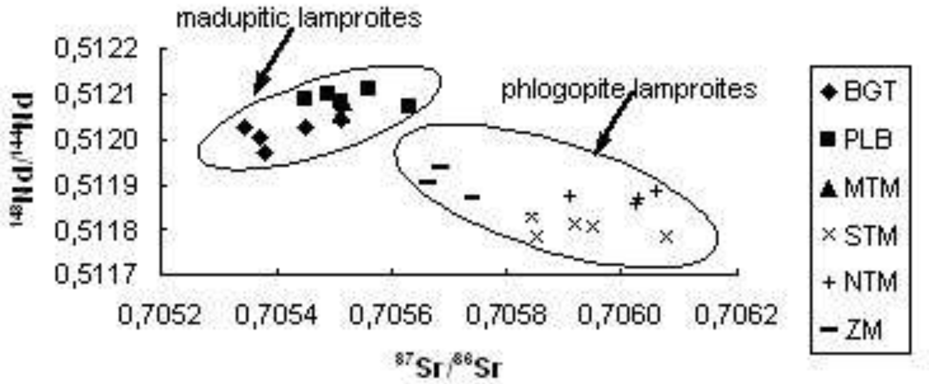

Fig. 4 $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ diagram. The transitional madupitic (BGT: Badgers Teeth, MTM: Middle Table Mountain) and madupitic lamproites (PLB: Pilot Butte) are characterized by higher 143Nd/144Nd and lower 87Sr/86Sr ratios than the phlogopite lamproites (ZM: Zirkel Messa. NTM: North Table Mountain). The olivine-bearing phlogopite lamproites from South Table Mountain (STM) have similar isotopic compositions to those of the phlogopite lamproites.

A combination of major, trace element and isotope ratio modeling [13] shows that the two major lamproite types in the Leucite Hills (i.e., phlogopite lamproite and madupitic lamproite) cannot be related to each other, either by fractional crystallization or by crustal contamination. Therefore, it is more likely that these lamproites represent primitive magmas derived from a heterogeneous mantle source.

9. Conclusions

Based on petrographic studies, the Leucite Hills lamproites are divided into two main groups: phlogopite lamproites and madupitic lamproites, and two sub-groups:
transitional madupitic lamproites and olivine-bearing phlogopite lamproites. The leaching test and analysis of the sedimentary enclaves and the separated minerals from lamproites show that the transitional madupitic lamproites resemble the madupitic lamproites in terms of their isotopic character. The olivine-bearing phlogopite lamproites share many geochemical features with the phlogopite lamproites and thus these two lamproite types can be grouped together. Finally, the madupitic lamproites and phlogopite lamproites form two distinct groupings on Sr vs Nd isotopic diagram indicating variations in chemical composition of their mantle sources.

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