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Potassic and ultrapotassic rocks: Compositional characteristics, petrogenesis, and geologic significance

Potassic and ultrapotassic rocks cover a wide range of compositions and are found as volcanic, hypabyssal, and plutonic bodies in a variety of geologic environments. On the basis of petrological parameters, they can be classified into several main groups that include the shoshonitic series, the Roman-type series, lamproites, and kamafugites. All of these are characterized by high to extreme enrichment in incompatible elements. Strontium, neodymium, lead, and oxygen isotopic ratios also are variable, a fact that gives evidence of complex genetic and evolutionary histories.

Petrological and geochemical data suggest that potassic and ultrapotassic magmas are generated in a heterogeneous, anomalous, phlogopite-bearing upper mantle at different pressures and activities of volatile phases. Together these factors produce a wide spectrum of petrologically and geochemically distinct magmas. Geochemical anomalies in the sources are believed to result from metasomatic processes related to the addition of small melt fractions and (or) gaseous fluids that are rich in potassium and incompatible elements. Geochemical and isotopic evidence indicates that these metasomatic agents may be derived either from sublithospheric mantle or from the dehydration and melting of oceanic slab and upper crustal material brought into the mantle by the subduction process. Subduction-related material can be recycled through the mantle for long times before being involved in the genesis of potassic magma.

Figure 1.—View of Mt. Vesuvius, Italy, the most famous active potassic volcano. Mt. Vesuvius has erupted explosively several times during the last 2,000 years. The most famous eruption was the one in 79 A.D., which destroyed the Roman cities of Pompeii and Herculaneum.

Gupta and Yagi, 1980). The most famous continental examples include those in central and southern Italy (fig. 1), the Eifel region in Germany, Uganda, Western Australia, Indonesia, southeastern Spain, western USA, and northeastern People's Republic of China. The Tristan da Cunha, Cape Verde, and Marquesas Islands are the best known oceanic examples. Shoshonitic rocks are associated with many continental and oceanic arcs.

The mineralogical, major-element, trace-element, and isotopic compositions of potassium-rich rocks are quite variable (see Yoder, 1986; Foley and others, 1987). Consequently, a plethora of genetic hypotheses have been proposed in the past in order to explain the many compositional oddities of these magmas. This, together with a confusing and abundant nomenclature that has produced a large number of local names, has contributed to rendering potassic rocks as mysterious petrological objects and to making the problem of their genesis obscure. Moreover, the discovery of diamonds in some potassic rocks, the association of potassic magmatism and rare-element mineralization, and the surge of hypotheses that small melt fractions of potassic composition have migrated through the mantle and have been a main process of mantle evolution together have increased the interest in potassic rocks well beyond the scope of simply explaining these exotic lithologies.

In this article, I will summarize some of the most prominent characteristics of potassic rocks, and I will outline a general picture of the petrogenetic hypotheses. I also will address the implications that studies of potassic magmatism have on the comprehension of large-scale evolutionary processes in the mantle.

Introduction

Potassium-rich rocks are limited in abundance but are widespread geographically. They include volcanic, hypabyssal, and plutonic bodies that are found in several tectonic environments, such as continental cratons, postcollisional areas, active orogenic belts, and, to a minor extent, oceanic intraplate settings (see, for example,

Classification and compositional characteristics

Conventionally, potassic rocks are defined as those that are characterized by a molar K_2O/Na_2O ratio that is around or slightly higher than unity at $MgO > 3$ wt percent. The restriction in the MgO content is required in order to exclude those rocks (such as some trachytes, dacites, and rhyolites) that have high K_2O/Na_2O ratios as a result of normal evolutionary processes and that may not imply a potassic nature for their parental magmas. The term "ultrapotassic" is reserved for the rocks that have $K_2O > 3$ wt percent and molar $K_2O/Na_2O > 2.5$. However, the terms "potassic" or "potassium-rich" often are used loosely to indicate both potassic and ultrapotassic rocks. This practice will be followed sometimes in this paper.

The wide compositional variability of potassic rocks has made their classification a difficult task, and a consensus is still far from being reached (Mitchell and Bergman, 1991). However, the classification schemes put forth by various authors (Sahama, 1974; Barton, 1979; Mitchell, 1985; Foley and others, 1987) recognize four main groups of potassic and ultrapotassic rocks. These include shoshonites, Roman-type ultrapotassic rocks, lamproites, and kamafugites. Kimberlites could be considered to represent an additional group, especially the group-two micaceous kimberlites, which have K_2O contents up to about 4 wt percent and K_2O/Na_2O ratios comparable to those of lamproites (for example, see Mitchell, 1988).

These groups do not cover all the potassic compositions that are found in nature. In fact, several rock types have transitional characteristics between the different groups, and their classifications and nomenclature are a matter of debate.

Mineralogy and major-element chemistry

Some representative major- and trace-element analyses for potassic and ultrapotassic rocks are given in table 1.

Shoshonitic rocks are the least enriched in potassium. They contain about 2–3 wt percent K_2O and have K_2O/Na_2O around unity. According to Morrison (1980), shoshonites should consist only of the rocks that are associated with calcalkaline volcanic rocks along convergent plate boundaries. Such rocks typically have high Al_2O_3 (14–20 wt percent), low TiO_2 (< 1.2 – 1.3 wt percent), and in the mafic range, a high abundance of CaO (10–12 wt percent). However, in more general terms (Joplin, 1968), shoshonites also include rocks that are moderately rich in potassium but are found away from volcanic arcs, such as those along the East Africa rift valley that represent the potassic equivalents of sodium-transitional rocks. The shoshonitic volcanic suites consist of shoshonitic basalts, latite, and trachyte to rhyolite. These rocks are mafic to intermediate in composition and range from slightly oversaturated in to slightly undersaturated in silica. They have a mineralogy that is dominated by diopsidic to salitic clinopyroxene and plagioclase. Olivine is a common phase in the most mafic rocks; biotite and sanidine are present in the intermediate rocks.

Roman-type ultrapotassic rocks make up the well-known leucite-tephrite, leucitite, and leucite-phonolite series. These rocks typically are found in the Roman Province of central Italy (Peccerillo and Manetti, 1985) and in some Indonesian volcanoes (for example, Varne and Foden, 1986). Recently reported occurrences include those in northeastern China (Wang and others, 1991) and central-eastern Paraguay (Comin Chiamonti and others, 1992). The Roman-type ultrapotassic rocks are undersaturated in silica, mafic to intermediate in composition, rich in Al_2O_3 (12–20 wt percent), and depleted in TiO_2 (generally < 1.2 wt percent). The mafic types have high CaO , typically around 10–13 wt percent; Na_2O is around 2–3 wt

percent. Leucite, plagioclase, and sanidine in the evolved rocks are the main salic phases. Pyroxene (Al-rich diopside to salite) is the most typical mafic mineral, whereas olivine is found in smaller amounts in the most mafic rocks. Nepheline is a common ground-mass phase. Phlogopite, biotite, pargasitic amphibole, titanium-magnetite, haityne, and apatite are present as minor or accessory minerals in rocks having various degrees of evolution. Roman-type ultrapotassic rocks commonly are associated with volcanic rocks that are less strongly enriched in K_2O . These are known as potassic series rocks and closely resemble arc shoshonites, even though the potassic series rocks are slightly more enriched in potassium.

Lamproites are found as lavas, tuffs, and hypabyssal bodies of ultramafic to intermediate composition. They have very high potassium contents and K_2O/Na_2O ratios and low Al_2O_3 , Na_2O , and CaO contents, generally lower than 10–11 wt percent, 1.5–2 wt percent, and 6–8 wt percent, respectively. MgO is high to very high, in places up to 20–25 wt percent. Most lamproites are peralkaline [molar $(Na_2O + K_2O)/Al_2O_3 > 1$]. The lamproite mineralogy consists of highly magnesian olivine, aluminum-poor diopsidic pyroxene, phlogopite, sanidine, and potassium-richrichterite. Leucite also may be present, whereas plagioclase typically is absent. Some lamproites contain uncommon titanium-, barium-, and zirconium-rich phases such as perovskite $[(Ca, Na, Fe^{2+}, Ce)(Ti, Nb)O_3]$, jeppite $[(K, Ba)_2(Ti, Fe^{3+})_6O_{13}]$, wadeite $(K_4Zr_2Si_6O_{18})$, shcherbakovite $[(Ba, K)(K, Na)Na(Ti, Fe, Nb, Zr)_2Si_4O_{14}]$, priderite $[(K, Ba)(TiFe^{3+})_8O_{16}]$, and armalcolite $[(Mg, Fe)Ti_2O_5]$ (Mitchell, 1985). These uncommon phases reflect the high degrees of enrichment in the component elements of the lamproitic magma. Some low- SiO_2 , high- MgO lamproites contain diamonds. Lamproites are present in continental intraplate environments such as Western Australia, Wyoming in the USA, and in postcollisional areas including Corsica, southeastern Spain, and central Italy. Some of them may contain mantle-derived xenoliths.

Kamafugites are named from the katungite-mafurite-ugandite series lavas cropping out in eastern Africa, which is the type locality for these rocks. Small amounts of kamafugitic rocks also are found in a few other places (see Foley and others, 1987), notably in central Italy, where they are associated with the Roman-type volcanic rocks (Peccerillo and others, 1988). Kamafugites are strongly undersaturated in silica and contain kalsilite and melilite as typical salic phases; leucite also may be present. Mafic minerals include magnesium-rich olivine and diopsidic to salitic pyroxene. Monticellite $(CaMgSiO_4)$, phlogopite, and perovskite may be present. Kamafugites share an ultrapotassic nature with lamproites, as well as low abundances of Al_2O_3 and Na_2O and high MgO , but kamafugites have high CaO (up to 18 wt percent). Xenoliths of mantle origin also are found in these rocks.

Minor- and trace-element geochemistry

In general terms, potassic and ultrapotassic rocks are characterized by high to extreme enrichment in the so-called incompatible elements. These are the elements having a charge and ionic size that make them unable to enter into the lattice of the main rock-forming minerals in the upper mantle. These incompatible elements are especially the large ion lithophile elements (LILE), potassium (K), rubidium (Rb), cesium (Cs), barium (Ba), thorium (Th), and uranium (U), and the light rare-earth elements (LREE), lanthanum (La), cerium (Ce), praseodymium (Pr), and neodymium (Nd).

A common graphic system used to display the absolute and relative abundances of elements in igneous rocks is one that gives normalized plots in which the elemental abundances of the rock are divided by the concentration values of a reference material. Chondritic abundances or calculated primordial mantle compositions are used generally as normalizing values. Figure 2 reports the patterns of

Table 1.—Major- and trace-element compositions of representative potassic rocks.

[SH-AA1 and SH-AA2: shoshonitic basalt and shoshonitic latite from the Aeolian arc; HKS-MA and HKS-PH: Roman-type high-potassium leucite tephrite and leucite phonolite from central Italy; KAM-SV and KAM-CU: kamafugitic rocks from central Italy; KAM-EA: kamafugitic rock from eastern Africa; LAM-CO and LAM-OR: lamproitic rocks from Corsica and central Italy; LM-AU1 and LM-AU2: low-silica and high-silica lamproites from Western Australia. Data from Bell and Powell (1969), Mitchell and Bell (1976), Peccerillo and others (1988), Jaques and others (1989), and author's unpublished data. Abbreviation: LOI, loss of ignition]

Sample	SH-AA1 1	SH-AA2 2	HKS-MA 3	HKS-PH 4	KAM-SV 5	KAM-CU 6	KAM-EA 7	LAM-CO 8	LAM-OR 9	LM-AU1 10	LM-AU2 11
SiO ₂	51.00	59.50	48.99	55.33	41.42	43.68	36.22	57.89	58.11	40.98	51.02
TiO ₂	0.90	0.69	0.70	0.60	0.67	1.15	4.76	2.37	1.43	2.65	1.41
Al ₂ O ₃	17.20	17.50	16.40	18.03	12.00	7.53	8.21	10.47	11.18	4.38	12.41
Fe ₂ O ₃	3.00	2.50	2.00	2.53	1.70	5.47	7.58	2.17	1.74	3.40	1.26
FeO	4.93	3.33	4.60	3.88	4.80	2.20	4.55	2.52	3.32	4.27	4.55
MnO	0.15	0.09	0.15	0.08	0.10	0.12	0.18	0.08	0.08	0.10	0.06
MgO	6.33	2.30	7.15	1.43	13.00	10.52	9.76	6.38	8.78	22.93	13.27
CaO	10.70	5.49	11.00	5.00	15.70	14.97	13.98	3.64	3.60	5.71	2.01
Na ₂ O	2.31	3.34	2.50	4.13	1.13	0.45	1.28	1.06	1.56	0.09	0.12
K ₂ O	2.33	3.77	6.00	8.81	8.41	9.88	7.29	10.49	7.43	4.26	7.06
P ₂ O ₅	0.46	0.41	0.50	0.43	0.40	1.14	1.09	0.82	0.70	0.88	0.59
LOI	0.70	1.00	0.20	0.70	0.77	2.90	3.07	2.07	2.07	8.19	5.47
Total	100.01	99.92	100.19	100.95	100.10	100.01	97.97	99.96	100.00	97.84	99.23
Cs			66.0	340	33	74		7	15	9.9	3.7
Rb	70	118	403	544	459	596	156	343	449	317	169
Sr	736	600	1150	1200	1834	3704	2531	812	646	930	276
Ba	1111	1412	880	880	750	4390	2500	1267	1175	835	1030
Th	16.1	26.0	40.0	184.0	38.0	137.0	29.0	41.0	109.0	16.4	21.0
U			10.5	30.0	10.5	28.0		5.5	18.0	2.2	3.6
La	51.0	63.0	66.0	178.0	96.0	254.0	197.0	183.0	149.0	118.0	51.0
Ce	103.0	118.0	133.0	355.0	193.0	578.0	404.0	302.0	315.0	312.0	108.0
Nd	49.0	43.0	62.0	0.0	90.0	232.0	0.0	111.0	165.0	82.0	43.0
Sm	9.0	10.1	12.5	22.6	20.3	41.0	20.4	19.0	29.0	11.2	5.9
Eu	2.20	2.20	2.10	3.00	3.33	7.60	4.98	2.50	3.30	2.60	1.26
Tb	1.00	1.10	0.77	1.12	1.41	2.90	1.79	0.80	1.10	0.81	0.39
Yb	2.49	3.33	2.13	3.44	3.12	2.60	1.11	1.10	1.90	1.09	0.45
Lu	0.37	0.70	0.33	1.32	0.46	0.36	0.13			0.13	0.03
Y	26	44	21		40	59		26	29	16	6
Nb	22	25	16	35	13	46	205	66	41	182	81
Ta	1.39	1.50	0.90	3.12	0.86	3.90	18.70	3.00	2.60	11.00	4.30
Hf	4.0	5.7	5.3	17.2	9.1	25.0	10.3	25.0	18.0	17.0	11.5
Zr	180	279	200		350	825	605	1351	787	575	367
Ni	69	10	93	12	153	80		271	307	980	560
Co	35	18	33	14	39	36	46	19	28	69	24
Cr	222	20	366	10	776	50	0	425	455	1180	890
Sc	33	15	31	7	19	18	25	10	15	15	5

incompatible elements, normalized to a primordial mantle composition, for representative potassic and ultrapotassic rocks. Roman-type rocks have fractionated (that is, steep) patterns showing high abundances of LILE and are relatively depleted in the high field-strength elements (HFSE), tantalum (Ta), niobium (Nb), zirconium (Zr), hafnium (Hf), and titanium (Ti). The deficiency in HFSE is typical of subduction-related rocks (Pearce, 1982) and also has been observed in potassic intrusive rocks and volcanic rocks that are associated with old orogenic areas in a number of places such as the Scottish Caledonides (Thompson and Fowler, 1986). Note that negative anomalies of HFSE are shown as well by shoshonitic rocks from the Aeolian islands (fig. 2A).

Kamafugitic rocks have variable incompatible-element patterns (fig. 2B). Those from eastern Africa have a convex-upward pattern with no titanium anomaly and high niobium and tantalum concentrations, and they closely resemble intraplate sodium-alkaline rocks (for example, Wood, 1979). By contrast, kamafugitic rocks from central Italy have negative anomalies of titanium, niobium, and tantalum and are indistinguishable from Roman-type high-potassium rocks.

Lamproites from zones of recent orogenesis, such as Corsica, central Italy, and southeastern Spain, have steep patterns showing negative anomalies of HFSE, barium (Ba), and strontium (Sr). In general terms, these patterns are very similar to those that typically

Figure 2.—Patterns of incompatible elements normalized to a primordial mantle composition (Wood, 1979) for some representative potassium-rich rocks. A, Shoshonitic (circles) and Roman-type (asterisks) rocks; data from table 1. B, Kamafugitic rocks from central Italy (circles) and eastern Africa (open squares); data from table 1. C, Lamproitic rocks from Corsica (triangles), central Italy (open squares), and southeastern Spain (asterisks); gneisses and schists

from basement in central Italy (circles); data from table 1, Venturelli and others (1984), Nixon and others (1984), and Sandro Conticelli (unpublished data, 1989). D, Lamproitic rocks from Western Australia (triangles) and Leucite Hills, Wyoming, in the western USA (circles); data from table 1 and Vollmer and others (1984).

are shown by upper crustal rocks like pelites or their metamorphic equivalents (fig. 2C) (see Conticelli and Peccerillo, 1992). Some of these features, such as negative spikes of niobium and strontium, also are observed in lamproites from Leucite Hills in Wyoming in the western USA and from Western Australia (fig. 2D).

Lamproites and kamafugites contain the highest abundances of the ferromagnesian trace elements nickel (Ni) and chromium (Cr) (sometimes more than 1,000 parts per million), but scandium (Sc) rarely exceeds 20–25 parts per million (Mitchell and Bergman, 1991).

In summary, the degree of enrichment in the incompatible elements of potassium-rich rocks essentially depends on their main petrological characteristics, especially the abundance of K_2O . In contrast, the style of incompatible-element enrichment, especially the LILE/HFSE ratios, seems to be a function of the geologic setting in which potassic rocks have been generated. This makes some rocks from different tectonic environments look similar in terms of individual major-element characteristics but strikingly different on the basis of some trace-element abundances and ratios. In particular, the neg-

ative anomalies of HFSE seem to be the main way to discriminate between intraplate and subduction-related potassic rocks. However, it must be noted that rocks that are very similar to Roman-type volcanic rocks, containing negative anomalies of HFSE, have been found recently in zones that are away from recent or active subduction (for example, the Sapucaí graben in Paraguay; Comin Chiamonti and others, 1992). This makes the relationship between geochemical signatures and tectonic settings more intriguing.

Strontium, neodymium, lead, and oxygen isotope geochemistry

Worldwide, potassium-rich rocks define two distinct trends on a $^{87}Sr/^{86}Sr-^{143}Nd/^{144}Nd$ diagram (fig. 3). One trend, formed by the Smoky Butte (Montana) and Leucite Hills (Wyoming) USA lamproites in the western USA and the Greenland lamproites, displays relatively low $^{87}Sr/^{86}Sr$ and variable but generally low neodymium isotopic ratios. The second trend is defined by the bulk of potassic

and ultrapotassic rocks and by group-two micaceous kimberlites. It shows more variable strontium and neodymium isotopic ratios and points to the isotopic composition of the upper crust.

Lead isotopic ratios are shown in figure 4. Central Italy potassic rocks have lower $^{207}\text{Pb}/^{204}\text{Pb}$ ratios than sodium-alkaline rocks of eastern Africa (Vollmer, 1977; 1989). Some lamproites from intra-plate settings, such as Western Australia, Gaussberg (East Antarctica), and the western USA, have a relatively wide range of $^{207}\text{Pb}/^{204}\text{Pb}$ and poorly variable $^{206}\text{Pb}/^{204}\text{Pb}$ isotopic signatures.

Oxygen isotopic ratios of potassic rocks are very variable. Much of this variability may be an effect of crustal contamination during the time that magma rises to the surface. However, mafic rocks also show a tendency to have high $\delta^{18}\text{O}$ with respect to other basaltic rocks. It is still under debate as to whether this depends on the characteristics of the source or on assimilation processes that significantly modify the oxygen isotopic composition but have minor effects on major- and trace-element chemistry and radiogenic isotopic composition (see Turi and others, 1986; Holm and Munksgaard, 1986; and references therein).

Petrogenesis

Historical perspective

The genesis of potassium-rich magmas has been one of the most debated issues of igneous petrology. The most puzzling characteristic that early petrologists considered was the high abundance of elements like potassium, rubidium, thorium, and uranium, which typically are enriched in crustal rocks, in mafic basaltic rocks undersaturated in silica of obvious subcrustal origin. Isotopic studies (Hurley and others, 1966) added additional problems by finding that some potassic rocks from central Italy had strontium isotopic signatures that were closer to crustal values than to mantle values, a finding confirmed by successive isotopic investigations (for example, Hawkesworth and Vollmer, 1979).

The first attempts to explain potassic magmatism date back to the beginning of the century when Daly (1910) suggested that potassic magmas were the products of the assimilation of carbonate rocks by "normal" sodium-alkaline basalts. Rittman (1933) applied Daly's hypothesis to Somma-Vesuvius and, by extension, to the "Mediterranean Series," as potassic rocks were named at that time. According to Rittman, potassic magmas were the products of the assimilation of carbonate rocks by trachytic magmas, which, in turn, were derived from a sodium-alkaline basalt by fractional crystallization processes. In this framework, the high content of potassium in the Somma-Vesuvius rocks was explained as being inherited from the evolved trachyte, whereas the undersaturation in silica was interpreted as being a product of carbonate syntesis. The hypothesis was strengthened by the presence of thick carbonate sequences in the basement rocks of Somma-Vesuvius and by the presence of numerous carbonate xenoliths within the lavas and pyroclastic materials of that volcano. However, this hypothesis was difficult to apply to eastern Africa because of the lack of limestone in that area. Accordingly, Holmes (1950) proposed the theory of the assimilation of granites by carbonatitic magmas for this region.

A syntectonic origin for potassium-rich rocks was the most widely accepted hypothesis until the 1960s when Savelli (1967) clearly demonstrated that potassic magmas have higher incompatible-element abundances than do both crustal rocks, especially limestones, and any common basaltic or trachytic liquid. Equally important, the assimilation of granite by a carbonatitic melt did not explain the high contents of ferromagnesian elements, such as chromium and

Figure 3.—Strontium-neodymium isotopic variations in potassic and ultrapotassic rocks. Data from Sandro Conticelli (unpublished data, 1989), Nelson and others (1986), Foley and others (1987), Nelson (1992), and references therein. Abbreviations: C., central; E., east; S., south; MORB, midoceanic-ridge basalt.

Figure 4.—Lead isotopic composition of potassium-rich rocks. Data from Vollmer (1977), Varne and Foden (1986), Nelson and others (1986), Nelson (1992), and reference therein.

nickel, in the most primitive potassic rocks. Furthermore, carbonatitic melts have temperatures (600–800 °C; Le Bas, 1987) that are similar to or lower than the granite solidus, and accordingly, they would be unable to assimilate granitic rocks. These lines of evidence led to ruling out assimilation as a first-order process responsible for the compositional features of potassic magmas.

In the following years, the hypotheses that became popular were based on gaseous transfer and metasomatic changes of either mantle- or crust-derived magmas. However, as noted by Carmichael (1967), it was a mystery as to how such a randomly operating process could produce similar compositions worldwide for potassic rocks.

Much more constrained models were proposed by Harris (1957), O'Hara and Yoder (1967), and Kay and Gast (1973). All these hypotheses shared the obvious assertion that, because of their mafic characteristics, the genesis of the primitive potassic magmas was to be placed within the upper mantle.

Harris (1957) suggested a zone-refining process for the generation of potassic magmas. Zone refining is a technique used in the steel industry to purify metal bars by melting them at one end and successively allowing the melt to cross the whole body of the metal by moving the heat source. This process exploits the property of impurities to enter preferentially into the liquid phase during the partial melting of metal or any crystalline solid. The zone-refining process applied to potassic magmatism suggested that a diapir of molten material ascending through the mantle would rise adiabatically by melting the roof rocks at its top and by crystallizing minerals at its base. The process would be able to sweep up all the impurities (that is, incompatible elements) from the mantle that was crossed by the diapir. As a result, the migrating melt would become enriched in incompatible elements and would attain ultrapotassic composition.

O'Hara and Yoder (1967) suggested that potassium and incompatible-element enrichment in subcrustal magmas may be derived from intramantle fractional crystallization of omphacitic pyroxene and garnet (eclogite fractionation) from a basaltic magma.

Finally, on the basis of trace-element quantitative modeling, Kay and Gast (1973) suggested that the high enrichment in incompatible elements and the strong fractionation of rare-earth elements (REE) in potassic basalts was an effect of very low degrees of partial melting of garnet-bearing peridotitic mantle. In order to obtain the LREE enrichment of some ultrapotassic rocks, they calculated that less than 1 percent of partial melting of a normal mantle was necessary.

These hypotheses raised a series of objections regarding both the geochemical and physical aspects of magma generation and segregation. However, the strongest drawback was that the high and variable strontium isotopic signatures of mafic potassic magmas were not explained. In fact, the general view prevalent at that time was that the mantle had a homogeneously low strontium isotopic composition, $^{87}\text{Sr}/^{86}\text{Sr}$ values clustering around 0.703–0.704. Nor was it likely that the radiogenic isotopic signatures were derived from crustal assimilation, as very large amounts of upper crustal material (sometimes higher than 70–80 percent) are necessary in order to modify significantly the radiogenic isotopic signatures of potassic magma. Obviously, this strongly conflicted with the undersaturation in silica and the mafic composition of many potassic rocks.

Mantle metasomatism and potassic magmatism

The advent of the concept of mantle metasomatism represented a turning point in our understanding of potassic and ultrapotassic magmatism. Studies of peridotitic xenoliths that have been torn from the upper mantle and brought to the surface by high-speed kimberlitic and alkalic basalt eruptions provided direct evidence for the presence of minerals rich in incompatible elements, such as phlogopite, amphibole, and apatite, within the upper mantle. In some cases, these minerals were found to be concentrated in veins, whereas in others they were dispersed throughout the rock body (see, for example, Bailey, 1982, and Menzies and Hawkesworth, 1987, for a review on mantle metasomatism).

Experimental investigations on natural rock systems (see Edgar, 1987; Edgar and Vukadinovic, 1992; Foley, 1992a, for a review) demonstrated that many ultrapotassic magmas were in equilibrium at high pressure with phlogopite-pyroxenite assemblages, rather than with normal peridotites. Additionally, theoretical geochemical modeling showed that an enriched mantle source was required in order to account for incompatible-element concentrations in potassic basalts.

These lines of evidence led to the conclusion that the upper mantle is heterogeneous at a small scale because of the introduction of metasomatizing agents that are rich in incompatible elements. However, the nature and origin of the metasomatizing agents are still a matter for discussion. In general terms, silicate melts or low-density gaseous fluids represent two extreme possibilities. Theoretical and experimental studies on fluid flow in porous mediums at high pressure (for example, Watson and others, 1990) suggest that low-viscosity silicate or carbonate melts migrate more easily than do gaseous fluids within the upper mantle.

According to McKenzie (1989), melt fractions smaller than 1 percent may be mobile within the upper mantle. These liquids are likely to be present within the sublithospheric mantle and, being less dense than the host rocks, have a tendency to separate from the matrix and migrate upward. As a result of their small volume, they cannot transport much heat and, accordingly, freeze readily when they enter into the relatively cool lithospheric mantle. Because these melts are formed by small degrees of partial melting of mantle rocks, they must be rich in incompatible elements and volatile compounds. In fact, both these components strongly partition into the liquid phase during partial melting, and their abundance in the melts increases as the degree of partial melting decreases. Metasomatic melts also are characterized by high ratios of elements having different degrees of incompatibility, such as Rb/Sr and Nd/Sm, which give high $^{87}\text{Sr}/^{86}\text{Sr}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios as they age.

On cooling, metasomatic melts yield veins that are rich in phlogopite and potassium-rich phases such as apatite. Gaseous fluids liberated during melt crystallization enter the wall rocks and cause pervasive metasomatism around the veins. Metasomatic minerals have lower melting temperatures than the surrounding mantle rocks; accordingly, crustal stretching or the uprise of isotherms due to an impinging hotspot, for instance, may produce preferential melting of veins and the consequent generation of potassic magmas.

The number of potassic veins present within the lithospheric mantle is a function of both the previous partial melting history of localized mantle domains and the time involved. Consequently, thick metasomatic layers can develop under stable cratons, whereas these layers are thin or lacking under young oceanic crust. This explains why potassic and ultrapotassic magmas are so rare in oceanic environments.

The origin of metasomatic agents is likely to vary in different tectonic environments. In cratonic areas, the agents may be derived from partial melting of the sublithospheric mantle. Indeed, mantle metasomatism in orogenic areas is largely a product of the fluids or melts that are released from the subducted slab. Therefore, it is not unreasonable to expect that metasomatic agents of different origins have distinct geochemical and isotopic compositions. Melts or fluids in orogenic environments are likely to be characterized by high LILE/HFSE ratios, possibly as a consequence of HFSE-rich residual phases being left in the slab during melting. This hypothesis nicely explains the high LILE/HFSE ratios of potassic rocks that are found in old or active orogenic areas. Additional complexities in subduction zones arise from the fact that a large variety of subducted material might be involved in metasomatism in the upper mantle. This material may include variously altered sea-floor basalts, deep-sea sediments, or, during continental collision, thinned continental crust

(Schreyer and others, 1987). In the last case, the metasomatic agents can have geochemical and isotopic compositions matching those of the upper crustal rocks, and these characteristics will be inherited by potassic magmas. For instance, the upper crustal geochemical and isotopic signatures observed in some potassic volcanic rocks (for example, in the central Italy and Corsica lamproites) strongly indicate the involvement of upper crustal rocks in mantle metasomatism (Peccerillo, 1990; Conticelli and Peccerillo, 1992).

By contrast, in intraplate environments, metasomatic agents probably show enrichment in all the incompatible elements, including HFSE. However, I must point out that subduction-related material can be recycled through the upper mantle and can be involved in potassic magmatism long time after its introduction within the upper mantle (Nelson, 1992). In this case, it is not surprising that potassic magmas having arc-type geochemical characteristics can be found away from any active or recent subduction zone.

Experimental petrology and potassic magmatism

Mantle metasomatism provides an adequate explanation for many geochemical and isotopic characteristics of potassic magmas. However, other relevant characteristics, such as the petrochemical diversity in terms of silica saturation and of the abundance of sodium (Na), calcium (Ca), and aluminum (Al), require integration of the metasomatic hypothesis. Experimental studies on synthetic and natural systems (Edgar, 1987; Edgar and Vukadinovic, 1992; Foley, 1992a) have provided a wealth of data that allow us to suggest an explanation for the problems.

Wendlandt and Eggler (1980) reported results of experimental studies on the $\text{KAlSiO}_4\text{-MgO-SiO}_2\text{-H}_2\text{O-CO}_2$ system, which corresponds to a metasomatized, potassium-enriched, phlogopite-bearing peridotite. They showed that, in the presence of low total amounts of volatile matter, small degrees of partial melting would produce potassic magmas. The stability field of enstatite increased as pressure increased and made these liquids vary from oversaturated to strongly undersaturated in silica as the depth of melting increased. This experimental work clearly highlights the roles of pressure and the fluid-phase composition in the generation of the variable degrees of silica saturation in potassic magmas. However, it does not explain other petrological characteristics such as the range of the sodium, calcium, and aluminum abundance from lamproites to Roman-type rocks and shoshonites.

One way to obtain sodium-, calcium-, and aluminum-poor magmas would be to assume that their source region was depleted in these components. Depletion in these elements within the upper mantle can be achieved by extracting basaltic liquids from a "fertile" lherzolite, one that has not undergone any previous melting event. Experimental studies (for example, Mysen and Kushiro, 1977) indicate that, during lherzolite melting, clinopyroxene and aluminum-rich spinel preferentially enter the liquid and leave a refractory harzburgitic residue that is depleted in Ca, Na, Al, and Sc and is enriched in MgO, Ni, and Cr. These characteristics are inherited by any magma that is formed by remelting of this source. Accordingly, lamproites are believed to be derived from a phlogopite- and (or) potassium-richrichterite-bearing harzburgite having a composition that results from the early extraction of basaltic liquids and is followed by, at some later stage, the metasomatic input of potassium and other incompatible elements (for example, see Foley and others, 1986, 1987). The range in the silica composition of lamproites has been attributed by Foley and others (1986) to the presence of different pressures of melting within a reduced upper mantle ($\text{H}_2\text{O-CH}_4\text{-HF}$ volatile composition), so that the low- SiO_2 , high-MgO lamproites are formed at higher pressures than are the high- SiO_2 varieties. The occurrence of diamond in the former type supports this hypothesis.

Kamafugites also have low sodium and aluminum and high MgO, which point to their generation within a refractory type of phlogopite-bearing mantle. However, their high content of CaO suggests that this element was introduced during the metasomatic event along with potassium and incompatible elements (Conticelli and Peccerillo, 1992). Furthermore, the strong degree of silica undersaturation indicates that the kamafugites were generated within the conditions of high pressure and high $\text{CO}_2/(\text{CO}_2+\text{H}_2\text{O})$, which are known to favor the generation of silica-poor, undersaturated melts (see Mysen, 1977; Brey, 1978; Wyllie, 1979).

Roman-type magmas have high CaO, Al_2O_3 , and Na_2O contents that require a "fertile" peridotitic source that has not undergone any significant extraction of basaltic melts before metasomatism and the generation of potassic magmas.

Concluding remarks

Geochemical and experimental studies have provided new insight into the petrogenesis of potassic magmas and have contributed to our understanding better the processes of mantle evolution. The following main points seem essential in order to understand the compositional characteristics and the geological significance of potassic magmas:

First, the metasomatic introduction of fluids or melts into the upper mantle is crucial for the production of an enriched source material. Metasomatic processes are believed to generate phlogopite- and potassium-amphibole-rich veins that melt readily in response to crustal stretching or an increase in temperature. The high strontium and low neodymium isotopic ratios that characterize most potassic magmas may be derived either from the time-integrated evolution of high Nd/Sm and Rb/Sr ratios of vein material or from the input of melts or fluids that are released by upper crustal material brought into the mantle as a result of the subduction process.

Second, the melting of a veined mantle produces petrologically variable potassic liquids that depend not only on the depth of melting, the composition and abundance of fluid phases, and the nature (fertile or refractory) of the mantle protolith but also on the degree of partial melting. The last determines the relative amount of the host rock that is involved in the melting (Bergman, 1987; Foley, 1992b). The distribution of incompatible elements in potassic magmas is likely to reflect the composition of the metasomatizing agents. These, in turn, have variable geochemical signatures that depend upon their source (that is, the subducted slab or sublithospheric mantle). However, residual phases can play a role as well during the melting of veins and thereby can determine some of the geochemical characteristics of potassic magmas (Foley and Wheller, 1990).

Third, the potassic liquids formed by the melting of veins also may have a role in determining the geochemical and isotopic features of other magmas, such as continental tholeiitic basalts, sodium-alkaline basalts, and calc-alkaline volcanic rocks (Ellam and Cox, 1991; Crisci and others, 1991). In fact, magmas of any composition ascending through the lithospheric metasomatic layer are likely to produce partial melting of the veins and consequent intramantle contamination of the uprising melt. Thus, the "potassic" geochemical signatures found in some calc-alkaline and tholeiitic rocks provide striking evidence that there are few or no magmas that represent a given melt generated by a single-stage process from given mantle rocks, but magmas represent a blend of melts that formed at different depths and by various degrees of partial melting (Anderson, 1990).

Fourth, additional compositional changes of potassic magmas may result from evolutionary processes at different depths. These generate residual liquids that are extremely enriched in many incom-

patible elements and in volatile phases. In some cases, the supersaturation in volatile phases is attained, and the separation of H₂O- and fluorine-rich phases may trigger huge explosive volcanic eruptions. The fluid phases that are separated from evolved potassic magmas are able to carry large amounts of incompatible elements into solution. The percolation of these fluids through wall rocks is responsible for the mineralization of rare elements (especially thorium, uranium, LREE, and antimony) that sometimes are associated with potassic volcanoes (Locardi, 1986).

Obviously, many questions that are relevant to the origin of potassic magmatism remain to be answered. In addition to the controversy about the type and composition of metasomatic agents and the role of residual phases during vein melting, a critical issue is the relationship between sodium-alkaline and potassium-alkaline magmas. Are the two types of alkaline magmas derived from different depths within the upper mantle, or do they reflect different types of metasomatism? Or are they related to different behaviors of metasomatic minerals during partial melting as a response to variable physiochemical conditions? This issue has been discussed by Ryabchikov and others (1982), Rogers and others (1992), and Edgar and Vukadinovic (1992), among others. The large spectrum of hypotheses suggested by these authors testifies that the topic is controversial and still is open to debate.

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