Silicic magmas derived by fractional crystallization from Miocene minette, Elkhead Mountains, Colorado

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Abstract

The rock association of minette with silicic lavas and intrusions (granites, syenites, dacites) is a common geologic feature in both collisional and extensional tectonic settings. Considerable doubt exists as to whether a genetic link exists between these mafic and silicic rocks. We describe a Miocene sill from NW Colorado which is a clear example of a mixed magma consisting of originally-liquid inclusions of minette in a silicic trachydacite host. Chemical and Sr, Nd and Pb isotopic data are consistent with derivation of the silicic host magma of the sill dominantly by fractional crystallization of the minette magma. Correlations between the elemental compositions of the rock types and their Sr and Nd isotopic ratios imply minor assimilation of continental crust with relatively low values of both $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$, concomitantly with fractional crystallization. The parental minette magma was probably derived by partial melting of subcontinental lithospheric mantle. While the sill was emplaced in a rift-like tectonic setting, the chemical and isotopic composition of the lithosphere-derived minette magmas (and hence the silicic fractionates) was largely independent of this setting, but dependent upon the composition and age of the lithospheric mantle and crust.

KEYWORDS: minette, trachydacite, mixed rock, silicic residue, isotopes, Rio Grande rift, Colorado.

Introduction

MINETTES are biotite-phyric mafic rocks of the calc-alkaline lamprophyre clan which differ chemically from basalts mainly in the greater abundance of K and other elements which are strongly incompatible during partial melting of the mantle (Rock, 1984; Thompson *et al.*, 1984). They occur mostly as dykes, and rarely as sills and lavas (e.g. Rock, 1984; Allan and Carmichael, 1984). Minettes are found in a range of tectonic settings, but characteristically occur as regional dyke swarms often associated with granitic (s.l.) or syenitic intrusions (or their volcanic equivalents) (Rock, 1984, 1987; Rock *et al.*, 1986; Leat *et al.*, 1987*a*). Considerable doubt exists as to whether minette magmas are capable of fractionating (with or without attendant assimilation of crust) to form the large volumes of silicic magma represented by such granitic and syenitic intrusions. There is no geological concensus that *any* particular group of evolved rocks are the products of fractional crystallization of minette magmas, perhaps because no large layered plutons or volcanic fields showing the evolutionary trend from minette to silicic residua

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have yet been described. Studies that support a parental role for minette magmas in the formation of *some* granitic (s.l.) or syenitic intrusions have concentrated on S. Scotland (Rock *et al.*, 1986; Macdonald *et al.*, 1986), NW Scotland (Thompson and Fowler, 1986), SW England (Leat *et al.*, 1987*a*; Thorpe, 1987), the Sesia–Lanzo Zone of the Alps (Dal Piaz *et al.*, 1979), and the Navajo volcanic field on the Colorado Plateau (Esperanca and Holloway, 1987). They include the following arguments. (i) The contemporaneity and close association of minette dykes and granite intrusions. Often the minette dykes occur in a zone around an individual granite intrusion or group of intrusions, but not within a central area within and adjacent to the intrusions (Rock, 1984; Macdonald *et al.*, 1986; Leat *et al.*, 1987*a*). The relationship is like the 'shadow zone' of geologically young basalt–rhyolite volcanic fields (Mahood, 1984), (ii) The existence of chemical zonation within individual minette dykes. Such zonation is widely attributed to crystal–liquid fractionation by flow differentiation, or *in-situ* crystal fractionation, or to the tapping of a pre-existing zoned magma chamber (Rock, 1984; Macdonald *et al.*, 1986). (iii) Trace-element arguments which seek to show that the trace element abundances and ratios of certain silicic plutons could be inherited, after fractional crystallization, from those of minettes (Thompson and Fowler, 1986; Thorpe, 1987; Leat *et al.*, 1987*a*). (iv) Experimental studies on minette melts (Esperanca and Holloway, 1987).

Several problems arise in assigning a parental role for minette magmas in the formation of some geographically associated granites. (i) Generally contrasting mode of occurrence (minette dyke swarms versus large coherent granite intrusions). The petrogenetic implications of this problem in S. Scotland have been pointed out by Rock *et al.* (1986). (ii) Differences in Sr and Nd isotopic composition between host rock and inclusions in at least one example of a mixed minette and silicic magma (van Bergen *et al.*, 1983), although Halliday *et al.* (1980) found potassic mafic magmatic inclusions in one granite from S. Scotland to have similar $^{87}Sr/^{86}Sr$ ratios to the host granite. (iii) High $^{87}Sr/^{86}Sr$ and other 'S-type' characteristics of some granites associated with minette intrusions—these strongly suggest an important role for crustal melting in the generation of the granites, but do not rule out a mantle-derived contribution (e.g. Halliday *et al.*, 1980; Darbyshire and Shepherd, 1985). Here we describe a convincing example of a series of rocks from minette, to its silicic residue after fractional crystallization, which occur together as components of a mixed magma sill in which blobs of the minette are scattered through a silica-rich, trachydacite host. Nine analysed samples form a suite in which the chemical variation can be explained by fractional crystallization. The samples all have similar and distinctive Nd, Sr and Pb isotope ratios. Subtle systematic relationships between those and indices of fractional crystallization in the suite indicate minor crustal assimilation.

The Elk Mountain sill

Elk Mountain (lat. 40° 34′, long. 106° 59′), 15 km NW of Steamboat Springs, Colorado, U.S.A., is a mesa, standing some 500 m above the surrounding area. It consists of a sill overlying Cretaceous sedimentary rocks. Because the sediments above the sill are not preserved, and its lower contact is obscured by talus, the estimated thickness of 150 m is a minimum. The sill forms part of the Elkhead Mountains volcanic field, which is volcanologically and geochemically diverse. It consists of over 200 separate dykes, sills, stocks, lavas and rare pyroclastic rocks (Buffler, 1967; Tweto, 1976). Overall chemical variation in this province defines a fractionation trend from mafic rock (minette and basalt) through andesite to dacite and rhyolite (up to 74% SiO_2) (Leat *et al.*, 1988). Luedke and Smith (1978) collated K–Ar age determinations which date the volcanic activity between 7.6 and 11.1 m.y. B.P. Post-Miocene erosion has removed some 0–400 m of poorly consolidated Miocene sediments and volcanic rocks from the Elkhead Mountains, and it is likely that the Elk Mountain sill was emplaced at a depth of about 300 m.

The Elk Mountain sill forms prominent cliffs on its western side, where it appears to have been emplaced as a single unit, with no visible subsidiary leaves, and no major internal contacts. The rock is fresh, with no silicification or veining, and little carbonation or hydrothermal alteration. The sill consists of a light grey prominently feldsparphyric host rock containing some 10% (by volume) of dark inclusions. These are flattened ellipsoids (relative axis lengths *c.* 1:2:3) with locally pronounced preferred orientation, probably a result of flow alignment. The dominant inclusion length is 5–15 cm; total size range is 1–200 cm.

Some inclusions show chilled margins typically 2 mm thick. Some inclusions have irregular margins suggestive of dividing of inclusions by pulling-apart by flow and of mingling of host and inclusion magma. These relationships suggest that the sill was emplaced as a mixed magma consisting of liquid mafic inclusions within a liquid leucocratic host.

Petrography

The host rock consists of phenocrysts of rounded alkali feldspar, fresh biotite (rich in opaque inclusions) and clinopyroxene in a fine-grained matrix dominated by elongate feldspar and equigranular clinopyroxene. There are probably xenocrysts of biotite and amphibole, mostly replaced by aggregates of very fine-grained Fe–Ti oxide. The inclusions are darker than the host rock and, both at the outcrop and in thin section, they are seen to consist of two types (herein called type Y and type X inclusions). Type Y inclusions are the least porphyritic rock type and contain mostly euhedral phenocrysts of biotite, clinopyr oxene, alkali feldspar, rounded quartz and small

Table 1. Chemical and isotopic analyses of host rock and inclusions

Sample	5LT149	5LT150	5LT153	5LT151	5LT156	5LT157	5LT155	5LT154	5LT152
n	1	2	2	2	3	2	3	2	2
Rock type	H	H	Y	Y	X	X	X	X	X
SiO_2	64.05	62.94	59.42	58.20	50.01	50.18	50.11	48.98	48.68
TiO_2	0.65	0.72	0.94	1.00	1.51	1.50	1.60	1.48	1.51
Al_2O_3	15.20	14.97	14.14	14.08	14.30	13.82	12.09	12.18	11.02
Fe_2O_3 (T)	4.00	4.29	5.29	5.70	8.87	8.71	8.59	8.42	8.14
MnO	0.065	0.058	0.086	0.063	0.126	0.139	0.199	0.121	0.204
MgO	2.75	3.35	4.88	5.48	7.76	8.20	9.30	10.11	10.28
CaO	3.84	4.25	5.70	5.88	7.49	7.79	8.51	9.37	11.12
Na_2O	4.87	4.53	4.05	4.03	3.26	3.03	2.81	2.17	2.53
K_2O	3.95	3.90	4.36	4.31	3.82	3.82	4.03	3.98	3.67
P_2O_5	0.44	0.46	0.69	0.75	1.30	1.17	1.22	1.31	1.07
Sum	99.80	99.47	99.54	99.49	98.45	98.36	98.46	98.12	98.22
LOI	0.49	0.56	0.91	0.85	0.84	0.85	0.69	0.89	3.22
Ba	3489	3420	3530	3749	3645	3586	3928	4236	3409
Be	2.2	2.3	3.0	3.0	3.1	3.0	3.9	3.1	3.4
Cr	103	150	234	246	226	315	577	464	779
Hf	7.4	6.9	9.5	9.2	9.2	9.1	12.6	10.1	10.6
Nb	13.9	14.7	17.9	16.7	28.1	27.0	20.7	16.9	17.4
Ni	36	45	71	72	115	134	129	160	229
Rb	47	48	58	58	57	58	65	56	59
Sc	8.9	10.2	13.3	13.8	21.6	23.2	24.4	28.4	23.8
Sr	1536	1551	1619	1682	1958	1815	1408	1680	1224
Ta	0.79	0.82	1.04	0.99	1.38	1.32	1.42	1.04	1.06
Th	5.4	4.4	5.0	4.5	4.9	5.1	4.2	4.0	3.6
U	2.5	2.2	1.6	1.3	1.9	1.8	0.9	1.2	1.4
W	4.5	5.6	5.6	8.6	2.4	2.9	-	12.5	7.4
Y	13	14	17	18	29	27	21	26	25
Zn	74	59	68	71	110	111	109	98	146
Zr	213	210	269	244	323	301	371	293	315
La	53	39	51	51	73	72	45	51	55
Ce	107	91	110	109	159	150	99	126	117
Nd	47	47	54	58	91	76	54	66	62
Sm	6.9	6.1	8.4	8.7	13.8	12.8	10.2	11.5	10.4
Eu	1.83	1.87	2.31	2.33	3.64	3.47	2.73	3.23	2.87
Gd	5.3	4.4	5.3	5.3	12.3	-	-	-	4.5
Tb	0.62	0.68	0.81	0.86	1.40	1.28	1.07	1.21	1.02
Yb	1.13	1.12	1.38	1.50	2.13	2.04	1.57	1.99	1.73
Lu	0.18	0.20	0.17	0.17	0.28	0.27	0.20	0.29	0.28
$^{87}Sr/^{86}Sr$	0.703961	0.703915	0.704037	0.704026	0.704131	0.704133	0.704002	0.704057	0.704067
$^{143}Nd/^{144}Nd$	0.512184	0.512214	0.512232	0.512245	0.512266	0.512253	0.512264	0.512248	0.512256
$^{206}Pb/^{204}Pb$	17.328	17.314	17.316	17.308	17.290	17.294	17.292	17.324	17.303
$^{207}Pb/^{206}Pb$	15.466	15.494	15.499	15.488	15.446	15.469	15.504	15.460	15.495
$^{208}Pb/^{204}Pb$	36.648	36.724	36.746	36.677	36.551	36.701	36.725	36.622	36.701

Major elements (weight %) measured volatile-free by XRF on fused glass discs (Morrison et al., 1987), n = number of determinations on separate discs (quoted values are averages). Trace elements (ppm): Ba, Be and Zn by ICP (Thompson et al., 1984); Cr, Hf, Sc, Ta, Th, U, W and REE by INAA (Leat et al., 1987); others by XRF on powder pellets. Isotopic ratios determined by McMaster University, 1σ errors; $^{87}Sr/^{86}Sr$ 0.000014; $^{143}Nd/^{144}Nd$ 0.000010, $^{206}Pb/^{204}Pb$ 0.010, $^{207}Pb/^{204}Pb$ 0.007, $^{208}Pb/^{204}Pb$ 0.020.

Rock types: H, trachydacite host rock; Y, type Y mafic inclusions; X, type X mafic inclusions (minettes).

Fe–Ti oxides. The equigranular matrix is dominated by alkali feldspar, clinopyroxene and biotite. Type X inclusions are more abundant than type Y inclusions. Type X inclusions occur both within the host rock, and within type Y inclusions, whereas type Y inclusions occur only within the host rock. Type X inclusions are good petrographic examples of minettes according to the criteria of Rock (1984) and are dominated by randomly-orientated euhedral biotite phenocrysts up to 3 mm long. Other phenocryst phases are clinopyroxene and Fe–Ti oxides. Possible former olivine phenocrysts or xenocrysts are now completely replaced by carbonate and chlorite. The matrix consists of alkali feldspar, clinopyroxene and biotite.

Elemental relationships of the mixed rock

Chemical data (Table 1) shows that type X inclusions have 48.6–50.2% SiO_2, and their high MgO contents (up to 10.3%) and high Ni and Cr abundances (up to 229 ppm and 779 ppm respectively) indicate that the magmas were not greatly fractionated from liquids in equilibrium with mantle peridotite. They are distinctly potassic ($K_2O > Na_2O$ wt. %) and plot as absarokites on a K_2O *v.* SiO_2 diagram. They lie within Rock's (1984) chemical screens for minettes. Variation diagrams (Fig. 1) show that they have diverse abundances of many trace elements (e.g. Zr, Rb, *REE*, Ta Y, Sr, U). Rock *et al.* (1986), Morrison *et al.* (1987) and Leat *et al.* (1987*a*) showed that such heterogeneity is a feature of many groups of geographically related contemporaneous minette intrusions.

The host rock to the mafic inclusions is mildly sodic ($K_2O < Na_2O$) and contains 63–64% SiO_2. It is therefore a trachydacite, verging on trachyte in the recommended IUGS nomenclature (Le Bas *et al.*, 1986). Despite the inhomogeneous nature of the sill, the chemical compositions of the analysed samples form continuous arrays which show excellent concomitant variation between, for example, Ni and SiO_2 and CaO (Fig. 1). In Table 2, we model the fractional crystallization of minette (sample 5LT154) to trachydacite (sample 5LT149) by a least-squares mixing calculation. Using a procedure similar to that of Thompson and Fowler (1986), the composition of a biotite–clinopyroxene cumulate nodule from a minette from the Elkhead Mountains with additional clinopyroxene and alkali feldspar is removed from 5LT154 to generate 5LT149. Additional biotite or Fe–Ti oxides do not improve the fit. The calculation shows that it is possible to model major element fractional crystallization from minette to the silicic rocks. However, the chemical arrays (Fig. 1) could be produced either by fractional crystallization of the mafic magma (type X inclusions) to give trachydacite residuum or by mixing between these two liquids. The choice between these two alternatives can be made by considering the type Y mafic inclusions which are intermediate in composition between host rock and type X inclusions with respect to most element abundances, but with the notable exception of K, which peaks in type Y inclusions (Fig. 1). This demonstrates that the composition of the type Y inclusions cannot be produced by mixing of the end-members. The data therefore appear to be consistent with a two-stage fractionation series: from magma similar in composition to that represented by type X mafic inclusions, through magma represented by type Y mafic inclusions, to the composition of the leucocratic host magma (Fig. 1). The first stage of fractional crystallization, from type X to type Y inclusions, resulted in enrichment in Si, Na, K, Al, Th in the daughter liquid, with depletion in Ti, Fe, Mn, Mg, Ca, P, *REE*, Cr, Ni, Sc, Ta, Nb, Zr, Hf, Y. Sr, Rb, U and Ba remained at approximately the same abundances. The second stage of fractionation, from magma like type Y inclusions to the trachydacite host magma, resulted in similar progressive enrichments and depletions, except that K, Sr, Rb and Ba were depleted in the residual liquid, and U was markedly enriched. Modelling these trace element variations by fractional cyrstallization is difficult, because of the scanty data for distribution coefficients for lamprophyric magmas (cf. Macdonald *et al.*, 1986; Thompson and Fowler, 1986).

A normalized plot of a wide range of elements (Fig. 2) in the two inclusion types and host magma shows that all three share distinctive geochemical features, reinforcing the hypothesis that they are genetically related. The large enrichment in Ba and K, relative to Rb and Th, is maintained as Ni and Cr fall throughout the suite, although the trough at Th is progressively diminished. High La/Ta, Hf/Zr and Hf/Ti ratios are present in all samples, and there is progressive development of a trough at P, and an enlargement of the trough at Ti. A slight trough at Sr in sample 5LT152 becomes an Sr spike in type Y inclusions and in the host magma. *HREE* are more strongly depleted in the daughter magmas than in the *LREE* (Fig. 2), so that chondrite-normalized *REE* diagrams become steeper with fractionation. None of the samples has an Eu anomaly.

The overall trend of chemical variation shows a lack of Fe-enrichment (Fig. 1), implying progressive decrease in magma density with fractionation. The rocks are alkaline with respect to

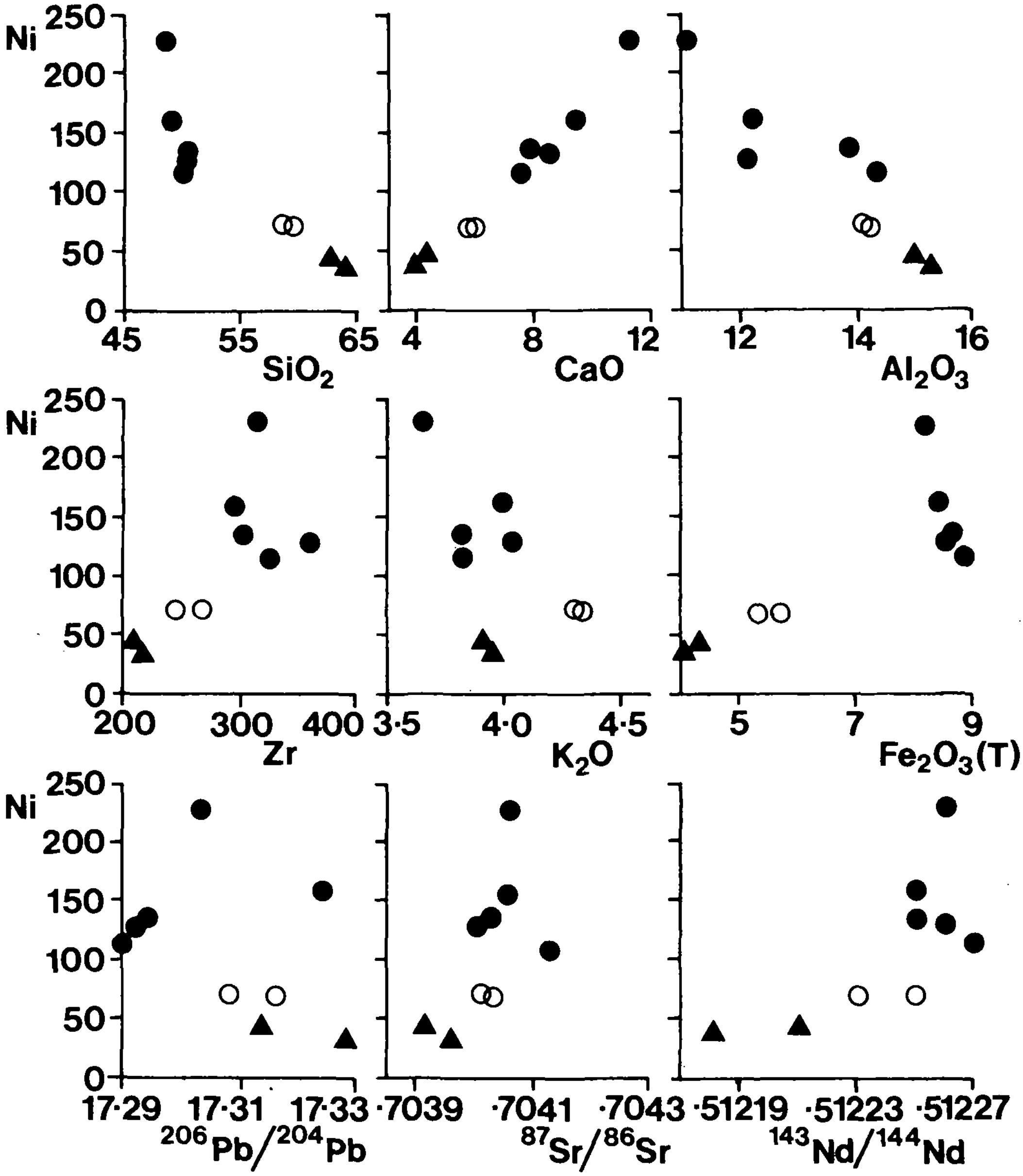

FIG. 1. Variation diagrams for the Elk Mountain sill, Ni and Zr in ppm, major elements in weight %. Triangles, trachydacite host rock; circles, mafic magmatic inclusions divided petrographically into: open circles, type Y; closed circles, type X.

alkali *v*. SiO_2 diagrams and shoshonitic to high-K on a plot of K_2O *v*. SiO_2 (Peccerillo and Taylor, 1976). The series is alkali-calcic (cf. Barker, 1981) and metaluminous, with a strong trend towards peraluminous compositions in the evolved magmas.

Isotopic characteristics

Both types of mafic inclusions, and also the leucocratic host magma, have very similar and distinctive Nd, Sr and Pb isotopic compositions (Fig. 1, Table 1). We think that this is the strongest

Table 2. Least-squares estimate of fractional crystallization required to derive trachydacite from minette magma.

	5LT149	5LT230	CPX	ALKF	5LT154 Obs.	5LT154 Calc.	Misfit
SiO_2	64.50	45.00	52.14	64.78	50.66	51.04	+ 0.38
TiO_2	0.65	2.37	0.46	0.11	1.53	1.45	- 0.08
Al_2O_3	15.31	11.06	1.85	19.03	12.60	11.27	- 1.33
Fe_2O_3	4.03	13.25	5.39	0.33	8.71	8.54	- 0.17
MgO	2.77	15.20	16.03	0.00	10.46	11.08	+ 0.62
CaO	3.87	8.21	22.45	0.56	9.69	8.54	- 1.15
Na_2O	4.90	1.40	0.68	3.29	2.24	1.99	- 0.25
K_2O	3.98	3.50	0.00	11.89	4.17	4.38	+ 0.21

$\Sigma R^2 = 3.76$. Mix: 5LT154 = 11.7% 5LT149 + 54.9% 5LT230 + 16.1% CPX + 17.3% ALKF.

5LT149, residual liquid (trachydacite host rock); 5LT230 mafic cognate block dominated by biotite and clinopyroxene, from minette, Brush Mountain, Elkhead Mountains; CPX, ALKF, clinopyroxene and alkali-feldspar compositions appropriate for minettes (Allan and Carmichael, 1984; Cundari, 1979); 5LT154, observed and calculated minette parent magma.

evidence that the silicic, intermediate and mafic samples represent magmas that are genetically related by fractional crystallization. The similarity in the Nd and Sr isotopic ratios of the samples is very clearly illustrated in Fig. 3, in which all the Elk Mountain samples fall within a tiny field which represents a very rare, distinctive composition. This probably excludes an origin for the silicic rocks in the sill by partial melting of *any* crustal composition. In Fig. 4, the range of isotopic composition of Elk Mountain is compared to the ranges found in Sr, Nd and Pb isotopic ratios in Cenozoic Volcanic rocks from the western United States. The very small ranges shown by the Elk Mountain sill are clearly shown. In order to argue that the silicic and mafic magmas of the sill were respectively generated by partial fusion of crust and mantle, it is necessary to plead the special circumstance that, coincidentally, both sources had almost identical Sr, Nd and Pb isotopic compositions. We conclude that the isotopic evidence strongly supports generation of the silicic magmas by fractionation of minette. All samples from the sill have $^{87}Sr/^{86}Sr$ between 0.70392 and 0.70414, and there is a slight overall *decrease* in $^{87}Sr/^{86}Sr$ with fractionation (Fig. 1). $^{143}Nd/^{144}Nd$ ratio decreases systematically (from 0.51227 to 0.51218) with fractionation (Fig. 1), but Pb isotopic ratios are essentially constant in all samples (Fig. 1, Table 1). These relationships are consistent with the view that the more fractionated rocks are somewhat contaminated by a rock type with low $^{143}Nd/^{144}Nd$ ratios, but also with low $^{87}Sr/^{86}Sr$. We therefore suspect that the Elk Mountain magmas were contaminated by continental crust with low $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ ratios, resembling Archaean granulite-facies acid–intermediate crust exposed in Scotland (Lewisian), and found among granulite-facies mid-crustal xenoliths in Tertiary and Quaternary lavas of the Snake River Plain, Idaho and the Leucite Hills, Wyoming (Fig. 3). The magmas did not assimilate significant amounts of ^{87}Sr-rich Proterozoic upper crust which underlies the area of the Elkhead Mts (Divis, 1977; Leat *et al.*, 1988, and unpublished data).

In Fig. 3, all Elk Mt. samples plot in a small area, well below the 'mantle array' and near: (i) Palaeocene lavas from Skye, Scotland, which have rather low abundances of many trace elements, and are thought to owe their low $^{143}Nd/^{144}Nd$ ratios to contamination of OIB-like magmas by Lewisian granulite facies crust (Thompson, 1982); (ii) Pliocene lavas from the Taos plateau, in the New Mexico part of the Rio Grande Rift, which perhaps are OIB-like magmas, selectively contaminated by unseen lower continental crust isotopically similar to Archaean granulite-facies crust of Scotland, Wyoming and Idaho (Williams, 1984; Dungan *et al.*, 1986); (iii) Tertiary and Quaternary

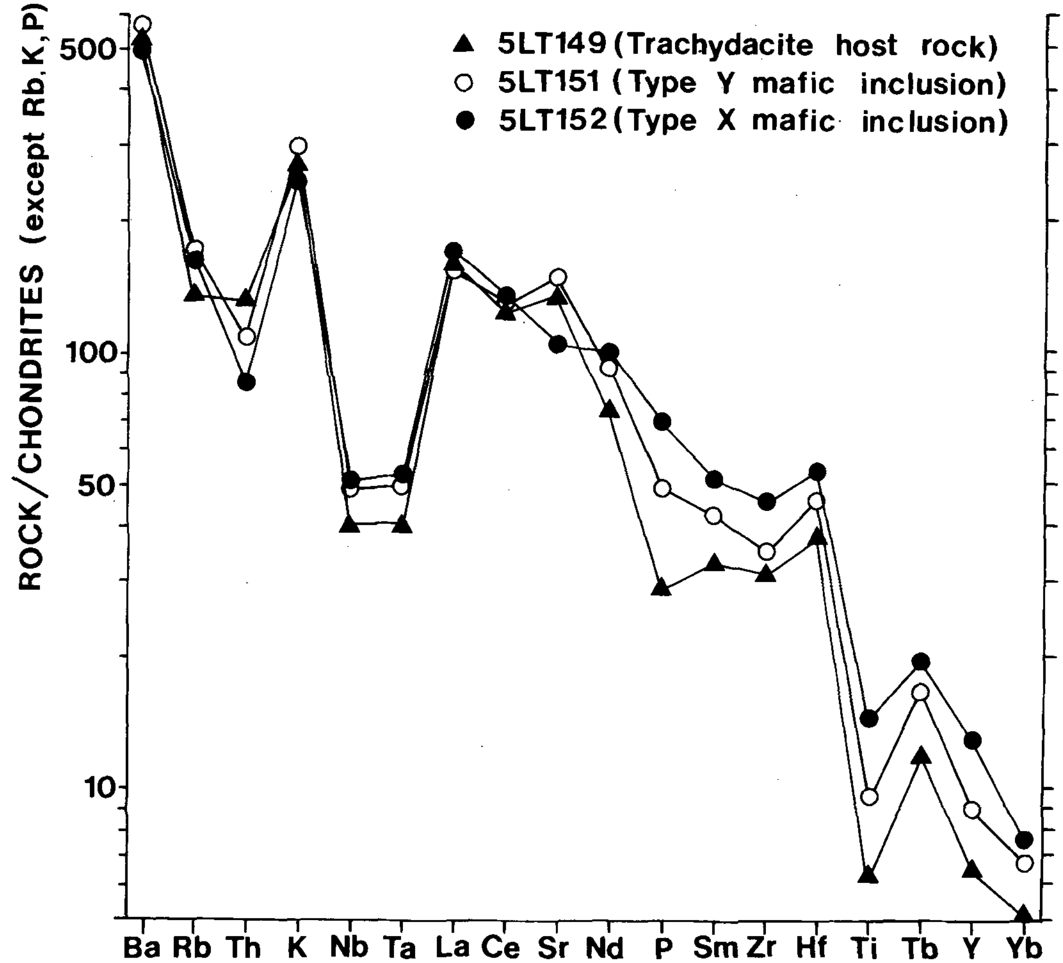

FIG. 2. Chondrite-normalized multi-element plots (Thompson, 1982) for host rock and type X and type Y inclusions. Symbols as in Fig. 1.

lavas from the Leucite Hills, Wyoming and Smokey Butte and the Crazy Mountains, Montana, thought to represent partial melts of continental lithospheric mantle underlying Archaean sial (Vollmer *et al.*, 1984; Frazer *et al.*, 1985; Dudas *et al.*, 1987); (iv) Xenoliths from a Tertiary dyke from Loch Roag, Isle of Lewis, Scotland, which Menzies *et al.* (1987) suggested are fragments of subcontinental lithospheric mantle. Leat *et al.* (1987*b*, 1988) documented the geochemistry of Miocene–Recent volcanic rocks in NW Colorado, to conclude that there are three groups of mafic rocks which cannot be related to each other by any combinations of fractional crystallization and assimilation of crust. Group 1 are OIB-like, probably derived by partial melting of OIB-source asthenospheric mantle. Group 2 are minettes, with high abundances of K, Ba, Zr, and low $^{143}Nd/^{144}Nd$ ratios. They are similar to mafic rocks of the Cretaceous–Recent Wyoming–Montana potassic province (Dudas *et al.*, 1987). The Elk Mountain minettes belong to this group. There is good reason to believe that the magmas of this group represent partial melts of aged subcontinental lithospheric mantle (Leat *et al.*, 1988). Group 3 rocks are olivine-phyric basalts having low Nb, Ta, K, and Rb abundances. Leat *et al.* (1988) thought that the voluminous Miocene examples of this group in NW Colorado were derived from an asthenospheric mantle modified by Cenozoic subduction of oceanic lithosphere. Group 3 magmas were also erupted in NW Color-

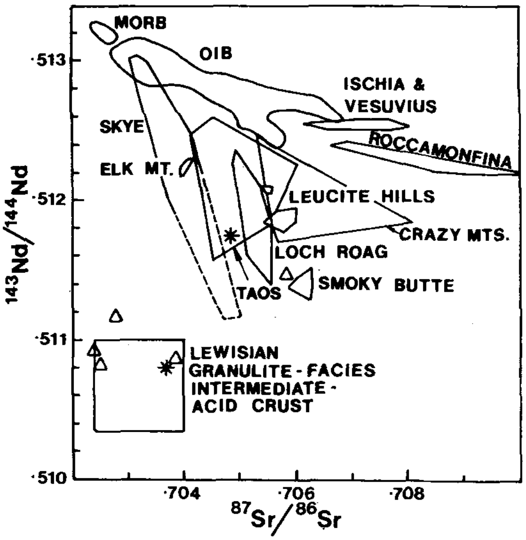

FIG. 3. $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ plot showing field for Elk Mountain sill, relative to selected fields of continental lavas, OIB, mantle xenoliths and Scottish Lewisian Archaean granulite-facies intermediate to acid crust. Labelled fields based on data from Hawkesworth and Vollmer (1979), Thompson (1982), Vollmer *et al.* (1984), Williams (1984), Frazer *et al.* (1985), Dungan *et al.* (1986), Menzies *et al.* (1987), and Dudas *et al.* (1987). The stars are acid-intermediate crustal xenoliths from the Leucite Hills, Wyoming (authors' unpub. data) derived from Archaean granulite-facies mid crust (Kay *et al.*, 1978); the triangles are selected samples of acid-intermediate Archaean granulite-facies mid crust occurring as xenoliths in the Snake River Plain lavas (Leeman *et al.*, 1985).

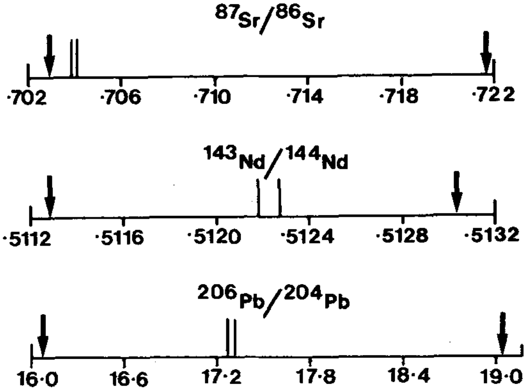

FIG. 4. Comparison of the wide range of Sr, Nd and Pb isotopic ratios for Cenozoic volcanic rocks from the western United States (arrows mark the maximum and minimum recorded values: critical references; Doe *et al.*, 1982; Menzies *et al.*, 1983; Leeman *et al.*, 1985; Frazer *et al.*, 1985), with the small range shown by the Elk Mountain sill samples (vertical bars).

ado during the Pleistocene, and similar magmas were erupted in the Pliocene Cerros del Rio volcanic field in New Mexico (Duncker *et al.*, 1987). These younger magmas appear to represent partial melts of lithospheric mantle. The complex relationships of this group 3 does not affect the interpretation that the group 2 minettes were generated by partial melting of lithospheric mantle.

Probably, the strongly-potassic mafic type X inclusions from Elk Mountain are partial melts of lithospheric mantle, and are local representatives of the isotopically distinctive province of lithospheric melts in Montana and Wyoming (Dudas *et al.*, 1987). Type Y inclusions and the host magma are likely to be the fractionates of such magma, contaminated progressively during this process by crust similar to that which Dungan *et al.* (1986) suggested had contaminated the magmas of the Taos Plateau, and which is sampled by the lavas of the Leucite Hills, Wyoming, and the Snake River Plain, Idaho.

Discussion

The Elk Mountain sill was emplaced at a time when this region of NW Colorado was experiencing crustal tension associated with the formation of the Rio Grande rift to the South (Tweto, 1979; Leat *et al.*, 1988). Widespread volcanism associated with crustal tension was dominated by basalts, some of which have OIB-like elemental and isotopic compositions as would be expected if they were derived from the asthenospheric mantle upwelling beneath the rifting lithospheric plate. These basalts therefore have chemical characteristics that are consistent with their crustal tectonic setting. In contrast, the Elk Mt. minettes (type X inclusions) were derived from ancient subcontinental lithospheric mantle with time-integrated *LREE* enrichments. These minettes—and therefore the associated type Y inclusions and host trachydacite magma—have chemical compositions which are independent of tectonic setting, but which are dependent only upon the composition and age of the underlying lithospheric mantle and of any crust which may have contaminated the liquids on their way to the surface.

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