

GEOCHEMICAL EVIDENCE FOR SEDIMENT RECYCLING FROM NORTH CAROLINA (U.S.A.) MINETTES

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ABSTRACT

Permo-Carboniferous minettes in Europe and in eastern North America, including the North Carolina Charlotte Belt minettes, were emplaced above the underthrust Gondwanaland Plate. In the western U.S., Tertiary minettes were emplaced above the underthrust Farallon Plate. With low-angle to horizontal subduction, oceanic plate rocks can move far inland beneath a continent. In the subhorizontal slab, small pressure variations and slowly rising temperature allow for incremental generation and efficient loss of progressively more refractory metamorphic fluids and partial melts. Minettes have strong shoshonitic affinities; high K_2O/SiO_2 , high Mg^* and K^* , strong enrichments in Ba, Sr, P, and F, and a rich, diverse trace-element assemblage, including "felsic" and "mafic" element enrichments in the same magma, are characteristic. The geochemical patterns in minettes are very difficult to reconcile with partial melting of garnet peridotite and fractional crystallization, even with recourse to metasomatism in the mantle. Typical minette-like geochemical patterns in deep-seated phenocrysts and strong evidence for rapid magma ascent suggest that primary geochemical patterns in minettes are not fundamentally altered by interaction with crustal rocks. Geochemical data from Charlotte Belt and other minettes, when compared to "average shale", suggest that ion exchange, absorption on clays, and precipitation of apatite could account for the main geochemical features of the original minette source. Pelagic clays, strongly modified by fluid and partial melt losses during subduction, are possible mantle source rocks. Losses of Fe-enriched (and P) partial melts could produce high MgO and Mg^* in the mantle residue; high K_2O and K^* could evolve through diagenetic K-enrichment in the original sediment, through K retention and Na loss related to feldspar stability, and through Na retention in residual clinopyroxene at high pressures.

Keywords: Permo-Carboniferous, minette, underthrusting, subduction, geochemical patterns, mantle source rock, pelagic sediment, composition modified, fluid losses, partial melts, North Carolina.

SOMMAIRE

Les minettes permo-carbonifères de l'Europe et de l'Est de l'Amérique du Nord, y compris celles de la ceinture de Charlotte dans la Caroline du Nord, ont été mises en place dans une plaque continentale sous laquelle la plaque de Gondwana s'enfonce par subduction. De même, dans l'Ouest des États-Unis, les minettes tertiaires ont été mises en place au-dessus de la plaque de Farallon, également en

relation de subduction. Si la zone de Benioff a un pendage faible ou nul, la plaque océanique peut être charriée sur une grande distance sous un continent. Dans une telle plaque océanique, de légères variations en pression et une augmentation progressive en température mènent à la formation et à la perte efficace de fluides métamorphiques et de magmas anatectiques progressivement plus réfractaires. Les minettes possèdent de fortes affinités shoshonitiques qui se caractérisent par un rapport K_2O/SiO_2 élevé, des valeurs élevées de Mg^* et K^* , de forts enrichissements en Ba, Sr, P et F, et un enrichissement en éléments-traces divers, y compris en éléments à affinité "felsique" et "mafique" dans le même magma. De telles tendances géochimiques sont difficilement réconciliables avec un modèle de fusion partielle d'une péridotite à grenat, suivie de cristallisation fractionnée, même avec recours à un métasomatisme dans le manteau. Des enrichissements géochimiques semblables à ceux des minettes dans les phénocristaux d'origine profonde et des indications sans équivoque de la montée rapide du magma font penser que la composition chimique primaire des minettes n'est pas sérieusement modifiée par contamination avec les roches crustales. La comparaison des données géochimiques, dans les minettes de Charlotte en particulier, à celles d'un shale moyen, permet d'expliquer, par échange d'ions, absorption sur les argiles et précipitation de l'apatite, les principaux aspects de la composition chimique de leur source. Une séquence d'argiles pélagiques, fortement modifiées par perte des fractions fluides et liquides au cours de la subduction, pourrait en être la source dans le manteau. Une perte en liquides silicatés enrichis en Fe et P pourrait expliquer les enrichissements en MgO et Mg^* dans le résidu dans le manteau. Les enrichissements en K_2O et en K^* pourraient résulter 1) d'un enrichissement diagénétique dans le sédiment originel, 2) de la conservation de K, avec perte de Na, due à la stabilité d'un feldspath, et 3) de la conservation de Na dans un clinopyroxène résiduel stable à haute pression.

(Traduit par la Rédaction)

Mots-clés: permo-carbonifère, minette, subduction, tendance géochimique, roche de source manteau, sédiment pélagique, composition modifiée, perte de fluid, fraction liquid, Caroline du Nord.

INTRODUCTION

Minettes, K-feldspar-biotite lamprophyres of shoshonitic affinity (Rock 1984), occur only in continental terranes as small-volume intrusive bodies or dyke swarms. Mantle and deep crustal xenoliths

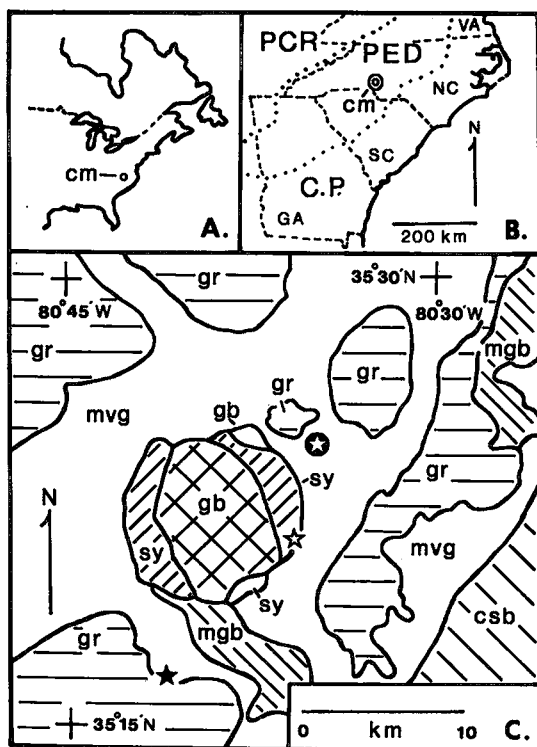


FIG. 1. Location and geological map, Charlotte Belt minettes. Cm (minette localities), PCR (Paleozoic Craton), PED (Piedmont; Paleozoic and Precambrian crystalline rocks), C.P. (post-Paleozoic Atlantic Coastal Plain sediments), open star (Concord minette), black star (Harrisburg minettes), and open star in black circle (city of Concord, NC); map legend: *Charlotte Belt* gr - 300 to 400 Ma granites; sy (syenite), gb (gabbro), mgb (metagabbro) - Concord plutonic suite (415 Ma); mvg - metavolcanics and gneisses, late Precambrian to Cambrian; *Carolina Slate Belt* (csb). Geology generalized from Goldsmith *et al.* (1978).

(Esperanca & Holloway 1986, Ehrenberg 1979) and geochemical arguments (Rogers *et al.* 1982, Roden 1981) indicate a direct mantle derivation for minettes. In regard to minettes and shoshonitic magmas, crustal assimilation and fractional crystallization are still controversial, being favored by some authors (Kramer 1976, Némec 1977, Rock 1984, Hyndman 1985, p. 409) and questioned (Bailey 1976) or rejected by others (Appelton 1972, Cox *et al.* 1976, Bachinski & Scott 1979, Jahn *et al.* 1979, Rogers *et al.* 1982).

Distinctive trace-element abundances (Rock 1984) and volatile contents suggest that minettes might, in part, originate by recycling of crustal material (Rogers *et al.* 1982, Thompson *et al.* 1984). Cosgrove (1972) related Permian minettes in southern England

to subduction on the basis of their shoshonitic affinities and tectonic setting. Minettes also have been interpreted to represent very small-fraction partial melts of previously metasomatized mantle (Rogers *et al.* 1982, Jahn *et al.* 1979).

A few Early Carboniferous minette dykes (Mauger, this issue) cut Charlotte Belt rocks near Concord, North Carolina (Fig. 1). Most exposures are saprolitic, but a few fresh outcrops can be found in quarries and streams. The Concord minette (Mauger, this issue) contains alkali feldspar, phlogopite, and abundant carbonates; clinopyroxene is conspicuously absent. Other minettes near Harrisburg (Fig. 1) have abundant clinopyroxene and phlogopite and much lower carbonate contents. In this paper I will briefly describe the tectonic setting and geochemistry of the Charlotte Belt minettes and suggest that subducted compositionally modified pelagic sediments are a possible mantle source-rock for minette magmas.

REGIONAL GEOLOGICAL SETTING

The Charlotte Belt minettes may represent sparse shoshonitic components of a major Carboniferous subduction-related plutonic arc in the southeastern Piedmont region (Fullagar 1971, Fullagar & Butler 1979, Sinha & Zietz 1982). These and other Permo-Carboniferous minettes in eastern North America and Europe were emplaced (Fig. 2) along the southern edge of Euramerica as the craton was being underthrust by the northwest-moving Gondwanaland Plate (Ross & Ross 1985). Late Paleozoic kimberlites (Zartman *et al.* 1967, Meyer 1976) were emplaced more toward the interior of the craton (Dawson 1980).

GEOCHEMISTRY AND PETROGENESIS

Minettes are geochemically linked with shoshonitic magmas (Rock 1984) and show close affinities with lamproites and highly potassic basalts. The geochemical patterns of minettes differ significantly from those of the common felsic and mafic rocks, kimberlites and the alkaline lamprophyres (Rock 1984). The Charlotte Belt minettes, like minettes elsewhere, exhibit the following distinctive geochemical characteristics (Table 1; Figs. 3, 4; Rock 1984): 1) Mg^* ($Mg/(Mg + Fe)$; atomic), K^* ($K/(K + Na)$; atomic), MgO/SiO_2 and K_2O/SiO_2 are unusually high for rocks saturated or nearly saturated in silica, and among the major elements, only Ti, K and Mg (Fig. 3) are strongly enriched with respect to Krauskopf's Average Shale (KAS; see Krauskopf 1979, app. III); 2) the P_2O_5/Ce wt. ratio (~ 25) is unusually low (Roden 1981) for igneous rocks with low to inter-

mediate SiO_2 but is equivalent to that of KAS; 3) *LREE* are strongly enriched, *HREE* are somewhat depleted, the *REE* pattern is steep ($[\text{La}/\text{Lu}]_{\text{CN}} = 35$) and there is no appreciable Eu anomaly (Figs. 3,4); 4) some *LIL* elements are very strongly enriched (Fig. 3) over KAS (Ba, Sr, Zr, and Hf) and a few are strongly depleted (Y, Ta, and Cs); 5) Ni shows very strong enrichment and trace elements of diverse geochemical affinities (Sc, Cr, Co, Mn, Cu, Zn, V, Rb, U, and Th) show $0.9 \times$ to $2 \times$ their abundances in KAS (Fig. 3); 6) anion formers, except for S ($0.2 \times$),

TABLE 1. GEOCHEMICAL DATA, CHARLOTTE BELT MINETTES

	Cm	Hm-2	Hm-5	Ave.
SiO_2	50.7	51.4	52.7	51.6
TiO_2	1.7	1.7	1.6	1.7
Al_2O_3	12.1	13.3	13.1	12.8
FeOt	6.2	6.4	6.4	6.3
MgO	8.3	7.4	7.0	7.6
CaO	5.2	5.1	5.0	5.1
Na_2O	1.9	1.4	1.8	1.7
K_2O	7.3	7.3	6.5	7.0
P_2O_5	0.4	1.1	1.2	0.9
H_2O	0.7	1.0	0.8	0.8
CO_2	5.2	0.7	0.9	2.3
F	0.4	0.5	0.4	0.4
Others	0.6	1.0	1.0	0.9
Total	100.8	98.3	98.4	99.1
Mg^*	0.70	0.67	0.66	0.68

	Cm	Hm-2	Hm-5	Hm-3	Ave.
Ba	3400	2420	2240	2900	2740
Sr	1180	1520	1775	1420	1475
Rb	140	175	155	180	163
Cs	0.7	2.0	1.8	1.7	1.6
Co	30	30	25	33	30
Ni	290	190	160	na	213
Cu	50	40	35	na	42
Zn	90	85	85	na	87
Cr	200	100	75	na	125
V	170	165	160	180	164
Sc	16	20	21	19	19
S	400	3500	3500	na	2467
Cl	na	400	290	310	333
Pb	na	15	<5	na	15
Th	11	11	12	11	11
U	*3	2.5	2.5	2.2	2.6
Hf	25	18	23	18	21
Ta	*0.9	0.6	0.7	0.6	0.7
Zr	710	710	740	na	720
Y	<20	25	25	na	<25
Nb	<20	<20	<20	na	<20
Mn	770	930	930	950	895
La	61	81	71	73	72
Ce	159	189	183	175	177
Nd	109	86	113	118	107
Sm	11	17	14	15	14
Eu	4.3	4.0	3.7	3.9	4.0
Dy	na	4.6	4.8	5.2	4.9
Tb	na	na	1.5	1.1	1.3
Yb	1.8	2.2	2.0	2.3	2.1
Lu	0.18	0.30	0.33	0.38	0.3

Cm is Concord minette; Hm-2, Hm-3, and Hm-5 are Harrisburg minettes (separate dykes); major elements are in wt.%, minors in ppm; others is $\text{BaO} + \text{SrO} + \text{MnO} + \text{Rb}_2\text{O} + \text{S}$.

Major elements by ICAPES and AA (Skyline Labs, Wheat Ridge, CO); minor elements in Harrisburg minettes by INAA (Los Alamos Nat. Lab., Los Alamos, NM); Ba, Sr, Rb, Co, Ni, Cu, Zn, Cr, V, S, Zr, Y, Nb, and Mn in Cm, Hm-2, and Hm-5 by ICAPES and AA (Skyline Labs); other minors in Cm by INAA (NC State Univ., Raleigh, NC) and other minors in Hm-2 and Hm-5 by INAA (Los Alamos Nat. Lab.).

* values estimated from analyses on carbonate-free sample.

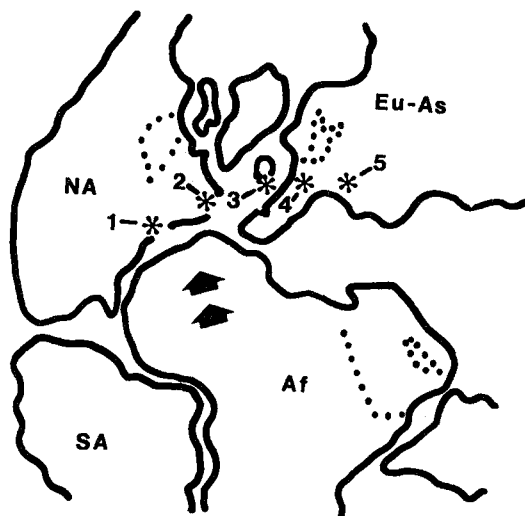


FIG. 2. Late Paleozoic minettes in relation to plate movements. Minette localities: (1) North Carolina plus Winnsboro, SC (Vogel & Wilband 1978, McSween *et al.* 1979) and Great Falls, MD (Reed *et al.* 1970); (2) New Brunswick, Canada (Bachinski & Simpson 1984); (3) others compiled by Rock (1984) include southern England, the Channel Islands and northwestern France; (4) central France; (5) central Europe. The minettes were emplaced into Hercynian and older terranes which lay above subducted oceanic lithosphere of the Gondwanaland Plate. Plate positions are for the Late Triassic (Smith *et al.* 1981).

are very strongly enriched (C and F) or strongly enriched (P) compared to KAS; and 7) $\delta^{13}\text{C}$ values (Table 3) for carbonates are 8 to 10 per mil lighter than average marine carbonates.

Compositions of deep-seated phenocrysts, Concord phlogopite (Table 2) and apatite from the Harrisburg minettes (average for 8 anal.: 0.8% SrO, 0.4% Cl, and $\text{Mg}^* = 0.75$), show that distinctive minette-like geochemical patterns (high Ba, Sr, Rb, *REE*, F, Ti, Ni, Cr, and Cl) were established before the magmas rose into the middle and upper crust. In addition, high magma-ascent rates (Ehrenberg 1979, Mercier 1979, Esperanca & Holloway 1986) and high liquidus temperatures (Esperanca & Holloway 1986, 1987) suggest that primary geochemical patterns in minette magmas are not altered fundamentally by interaction with crustal rocks. Abundant primary carbonates in the Concord and in other minettes (Kramer 1976, Rock 1984, Némec 1975) suggest that minette magmas may not always have high water/carbonate ratios (Bachinski & Scott 1979); however high $a_{\text{H}_2\text{O}}$ is important in stabilizing phlogopite at lower to mid-crustal pressures (Esperanca & Holloway 1987).

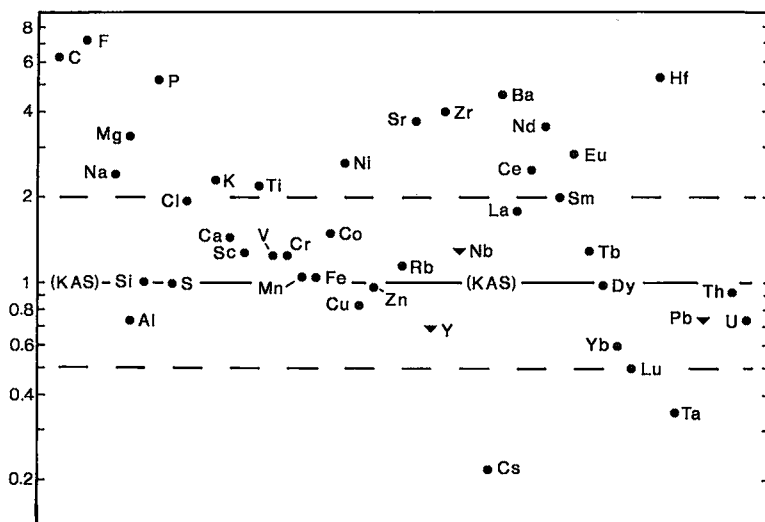


FIG. 3. Spider diagram, Charlotte Belt minettes. Average of 3 or 4 analyses (Table 1) plotted relative to Krauskopf's (1979) Average Shale (KAS). Triangular points (Y, Nb, Pb) show upper limits.

TABLE 2. CHEMICAL DATA (PPM) FOR PHLOGOPITE IN CONCORD MINETTE

Mg*	Cu	Zn	Ni	Cr	Co	Ba	Sr	Rb	
1) na	10	200	480	590	70	6350	260	230	
2) 0.9	50	90	1500	1100	40	290	*800	125	
3) 0.8	na	na	690	450	50	na	na	na	
Ce	Sm	Cs	Th	Hf	La	Nd	Eu	Lu	Sc
1) 31	2.8	1.3	4	6	14	29	1.0	0.08	13

1) separate used for K-Ar age, flakes were mainly between 0.15 and 0.21 mm in dia.; 2) coarse phenocrysts, 0.4 mm; 3) flakes between 0.2 and 0.4 mm in dia. REE, Cs, Sc, Th, and Hf by INAA (NC State Univ., Raleigh, NC); others by AA or ICAPEP (Skyline Labs, Wheat Ridge, CO).

* sample contained 0.54 wt.% P, so ≤ 300 ppm of Sr could be due to apatite (assuming ≤ 1 wt.% SrO in apatite).

TABLE 3. CARBON AND OXYGEN ISOTOPES, CHARLOTTE BELT AND OTHER LAMPROPHYRES

	$\delta^{13}\text{C}$ PDB	$\delta^{18}\text{O}$ SMOW
Cm dolomite	-8.9	+8.0
calcite	-10.0	+12.4
Cm dolomite	-9.2	+8.3
calcite	-9.4	+11.8
Hm-2 calcite	-10.9	+6.4
siderite	-11.6	+8.1
Hm-5 calcite	-10.7	+5.8
siderite	-10.3	+6.6
Other Lamprophyres	$\delta^{13}\text{C}$ PDB	ref.
3 minettes	-12 to -6	Kramer (1976)
3 lamprophyres	-6.6 to -6.0	Frenzel (1971)

calcite - CO₂ evolved during a first 24-hr. of reaction with phosphoric acid; dolomite - CO₂ evolved during a second 24-hr. reaction; siderite - CO₂ evolved during a second 3-day reaction (Long and Warneke, analysts: Univ. of Arizona, Lab. Isotope Geochemistry).

Cm, Concord minette; Hm-2 & Hm-3, Harrisburg minettes

AN ORIGINAL SEDIMENTARY SOURCE FOR MINETTES

Deep-sea muds are suggested as possible contributors to the mantle source for minette magma. Horizontal to very low-angle subduction (Sacks & Snoke 1984, Bird 1984, Lipman 1980) provides a mechanism for moving subducted sediments inland beneath areas of collisional tectonic activity or beyond. The subducted slab may remain in place indefinitely, depending on the evolving density contrast between slab and mantle. Compaction, pore-water expulsion, progressive metamorphism to garnet peridotite P - T conditions, and efficient extraction of dehydration fluids and partial melts would strongly modify the original bulk composition.

Enrichment in K and high K^* (>0.6) are fairly common in clay-rich sediments (Engle *et al.* 1974, Mielke 1979). During compaction and diagenesis, K from decomposed alkali feldspars is fixed in smectite as interlayered illite (Weaver & Beck 1971, Hower *et al.* 1976); K-rich zeolites may also develop from air-fall ash units. With deeper burial, Na is selectively expelled in pore waters and dehydration fluids until a plagioclase is stabilized at low to medium metamorphic grades (Hower *et al.* 1976, Volfinger 1976). At higher pressures, plagioclase breakdown and sanidine stability (Boettcher *et al.* 1984) might further raise K^* of the residual solids. Higher-pressure partial melting might also result in K-enriched melts as Na is retained in a residual Na-bearing clinopyroxene. Diagenesis and metamorphism probably effect insignificant changes in Mg content and Mg^* . However, through extraction of high-pressure dehydra-

tion fluids and early partial melts enriched in Fe, the subducted sediment could eventually become strongly enriched in high-Mg* mafic silicates. Thus later partial melts associated with decomposition of high-Mg* phlogopite could be enriched in Mg and K. Mantle xenoliths attributed to Fe-Ti-alkali metasomatism (Ehrenberg 1979), Fe-rich amphibole-cpx-apatite xenoliths (Wass 1979, Wass & Rogers 1980), the common occurrence of reverse zoning (Mg-enriched zones around Fe-rich cores in mafic silicate phenocrysts) in shoshonitic magmas (Pe-Piper 1984) and minettes, and certain enigmatic Fe-Ti- and P-rich rocks (Philpotts 1967, Park 1961, Lyons & Clabaugh 1973) could be evidence of such mantle-derived Fe- and P-rich partial melts. The ilmenite- and apatite-in curves ($P < 20$ kbars) associated respectively with minette (Esperanca & Holloway 1987) and high-K latite (Esperanca & Holloway 1986) bulk compositions have steep (but negative) dP/dT , and both phases crystallize at slightly lower temperatures (1020 to 1040°C) than phlogopite. Phosphorus-enriched early Fe-rich partial melts are readily explained if these relations hold for higher pressures. Derivation of a P_2O_5/Ce weight ratio of about 25 from a compositionally modified sedimentary source is straightforward and does not require prior enrichment of Ce in the mantle nor fractional crystallization of apatite from the magma (Roden 1981). Early separation of apatite is especially unlikely in view of the experimental results of Esperanca & Holloway (1986).

Most clay-rich sediments contain primary oxidized Fe and Mn compounds, organic C, and marine carbonate. Diagenetic oxidation of the organic fraction is effected by reduction of Fe and Mn (Weaver &

Beck 1971). The resulting total-rock carbonate would have $\delta^{13}C < 0$ as is the case for the Concord and other minettes (Table 3), and subsequently the Mn and Fe would be readily extractable as 2^+ ions in dehydration fluids and early partial melts.

Barium, Sr, P, and F (Table 1; Fig. 3) show strong enrichments in minettes (Rock 1984) and in pelagic clays (Hole *et al.* 1984, Bostrom *et al.* 1974, Mielke 1979). Barium is strongly absorbed on smectite (Bohn *et al.* 1985, Chap. 6) and is precipitated as barite (Piper 1974, Guichard *et al.* 1979). Strontium, along with F and P, is strongly absorbed on smectite and is enriched in deep-sea carbonates (Mielke 1979) and marine phosphorite. These elements would be held tightly through diagenesis and metamorphism. Some P, F, Sr, and Fe would be lost through early melting of apatite and Fe-Ti oxides, suggesting that an appropriate source material, such as compositionally modified clay sediment, was originally even more strongly enriched in these elements than the derived magma.

As 3^+ ions, REE and Y are strongly absorbed on deep-sea smectite ($5 \times$ KAS, Piper 1974) and on smectite ($2 \times$ KAS, Cullers *et al.* 1975) formed *in situ* from volcanic glass, and variably enriched ($0.5 \times$ to $2 \times$ KAS) in illites and in marine apatite ($2 \times$ to $6 \times$ KAS; Altschuler 1980, Fleet 1984). Diagenesis (Chaudhuri & Cullers 1979) and metamorphism probably would have little effect on REE abundances. Clay-rich sediments are more enriched in REE ($2 \times$ to $5 \times$ KAS) than minettes ($1 \times$ to $2 \times$ KAS), but (La/Lu)CN are lower than those of minettes. With partial melting, residual garnet and perhaps clinopyroxene could generate the higher (La/Lu)CN, the strong enrichment in LREE, and

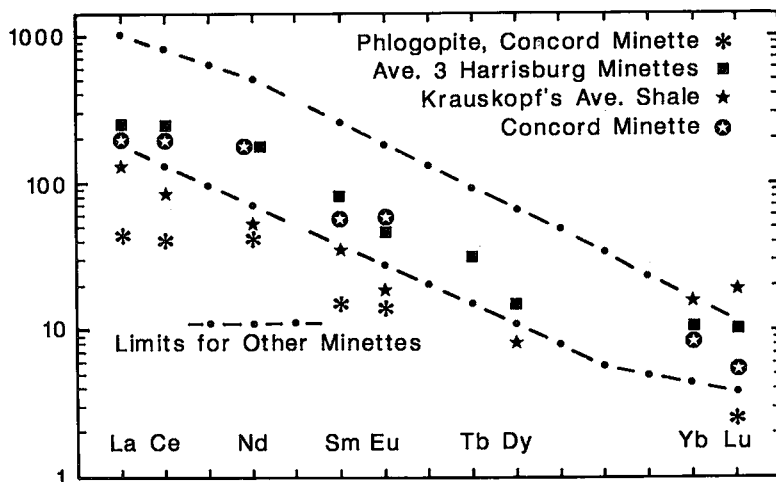


FIG. 4. Chondrite normalized REE diagram for Charlotte Belt minettes. Limits for other minettes are from Rock (1984). Analytical data are listed in Table 1, and chondrite REE abundances from Masuda *et al.* (1973).

the depletion in *HREE* and Y observed in the Charlotte Belt (Table 1; Figs. 3, 4) and other minettes.

The abundance patterns of the 3rd-row transition elements Sc–Zn, the mafic (Cr, Ni and Co) and felsic (Rb, Th, U, Zr, Hf) trace-element enrichments in the same rock, and the crustal-like Th and U values (McLennan *et al.* 1980) suggest that ion exchange involving clays (Bohn *et al.* 1985) was probably the dominant process of metal concentration in the source material of minettes. Extra Ti, Zr, and Hf may have been added in felsic volcanic ash, and Ta and Nb are generally depleted in deep-sea mud sediments with no terrestrial source (Hole *et al.* 1984). Abundances of 3rd-row and heavier transition elements (Ta, Nb, Th, U, Zr, and Hf) should remain relatively unmodified until partial melting, but other elements such as S and Cs, and to a lesser extent Rb, might be lost in low-pressure dehydration fluids (Volfinger 1976).

DISCUSSION

Geochemical mass-balance studies (Reymer & Schubert 1984, Kay 1980, 1984) and geologic and geophysical investigations show that sediments are routinely subducted (Westbrook *et al.* 1982, Davey *et al.* 1986, Moore *et al.* 1986). Pelagic and hemipelagic muds resting directly on the oceanic crust are the most likely sediments to be subducted, the detachment decollement typically lying above the pelagic sediment zone. In the region of low geothermal gradient beneath a stable craton, a subhorizontal subducted slab would heat very slowly; chemical fractionation could be very efficient because dehydration fluids and partial melts would be generated and lost as temperatures and pressures increased very slowly.

Late Paleozoic minettes in eastern North America and Europe and Tertiary minettes and shoshonitic rocks in the western U.S. (Rowell & Edgar 1983) were emplaced above underthrust oceanic plates. Even a Tertiary minette in the Black Hills, South Dakota (Kirchner 1979) was probably emplaced above the eastern edge of the Farallon Plate (Bird 1984). Thus minettes, like other shoshonitic magmas, are closely related to subduction (Thompson *et al.* 1984, Morrison 1980, Jaques 1976, Peccerillo 1985, Civetta *et al.* 1984). Richly diverse trace-element characteristics, elevated fO_2 , variable and somewhat radiogenic Sr^{87}/Sr^{86} initial ratios (Roden 1981), $\delta^{13}C < O$ (Kramer 1976) and $\epsilon_{Nd} < O$ (Albarede & Weisbrod 1981) are primary magma characteristics. Minette magmas rise rapidly, precluding much chemical interaction with crustal rocks; magma temperatures are too high for minettes to be late-stage derivative magmas, and geochemical patterns are not related to crustal assimilation nor to com-

monly occurring potentially parental felsic or mafic magmas (Rock 1984). Subducted compositionally modified deep-sea mud sediments are suggested as a possible source rock for minettes, and the K-rich lamproites might derive from a more refractory sedimentary source subducted deeper into the mantle.

ACKNOWLEDGEMENTS

Sharon Bachinski helpfully reviewed an early version of this work. R.F. Martin and A.D. Edgar encouraged the author to write a "much shortened" version (this paper) of his ideas on geochemistry, plate tectonics, and minette genesis. Todd Solberg helped the author to learn how to operate the VPI & SU electron microprobe. The East Carolina University Research Committee helped to fund this project.

REFERENCES

- ALBAREDE, F. & WEISBROD, A. (1981): Hercynian synorogenic lamprophyres from the SE Massif Central (France): evidence for equilibrium of Nd isotopes and REE with surrounding granitic rock. *EOS, Trans. Amer. Geophys. Union* **62**, 1076.
- ALTSCHULER, Z.S. (1980): The geochemistry of trace elements in marine phosphorites; Pt. 1, Characteristic abundances and enrichment. In *Marine Phosphorites; Geochemistry, Occurrence, Genesis* (Y.K. Bendor, ed.). *Soc. Econ. Paleon. Mineral., Spec. Pub.* **29**, 19-30.
- APPLETON, J.D. (1972): Petrogenesis of potassium-rich lavas from the Roccamonfia Volcano, Roman Region, Italy. *J. Petrology* **13**, 425-456.
- BACHINSKI, S.W. & SCOTT, R.B. (1979): Rare-earth and other trace element contents and the origin of minettes (mica-lamprophyres). *Geochim. Cosmochim. Acta* **43**, 93-100.
- & SIMPSON, E.L. (1984): Ti-phlogopite of the Shaw's Cove minette: a comparison with micas of other lamprophyres, potassic rocks, kimberlites, and mantle xenoliths. *Amer. Mineral.* **69**, 41-56.
- BAILEY, D.K. (1976): Experimental petrology. Application of experiments to alkaline rocks. In *The Evolution of Crystalline Rocks* (D.K. Bailey & R. MacDonald, eds.). Academic Press (London), 419-469.
- BIRD, P. (1984): Laramide crustal thickening event in the Rocky Mountain Foreland and Great Plains. *Tectonics* **3**, 741-758.
- BOETTCHER, A.L., GUO, Q., BOHLEN, S. & HANSON, B. (1984): Melting in feldspar-bearing systems to high pressures and the structures of aluminosilicate liquids. *Geology* **12**, 202-204.

- BOHN, H.L., MCNEAL, B.L. & O'CONNOR, G.A. (1985): *Soil Chemistry (2nd ed.)*. John Wiley & Sons, New York, NY.
- BOSTROM K., JOENSUU, O. & BROHM, I. (1974): Plankton: its chemical composition and its significance as a source of pelagic sediments. *Chem. Geol.* **14**, 255-271.
- CHAUDHURI, S. & CULLERS, R.L. (1979): The distribution of rare earth elements in deeply buried Gulf-coast sediments. *Chem. Geol.* **24**, 327-338.
- CIVETTA, L., DELCARMINE, P., MANETTI, P., PEC-CERILLO, A. & POLI, G. (1984): Petrology, geochemistry, and Sr-isotope characteristics of lavas from the area of Commenda (Mts. Vulcini, Italy). *Bull. Volcanologique* **47**, 581-595.
- COSGROVE, M.E. (1972): The geochemistry of the potassium-rich Permian volcanic rocks of Devonshire, England. *Contr. Mineral. Petrology* **36**, 155-170.
- COX, K.G., HAWKESWORTH, C.J. & O'NIONS, R.K. (1976): Isotopic evidence for the derivation of some Roman Region volcanics from anomalously enriched mantle. *Contr. Mineral. Petrology* **56**, 173-180.
- CULLERS, R.L., CHAUDHURI, S., ARNOLD, B., LEE, M. & WOLF, C.W., JR. (1975): Rare earth distributions in clay minerals and in the clay-sized fraction of the Lower Permian Havensville and Eskridge shales of Kansas and Oklahoma. *Geochim. Cosmochim. Acta* **39**, 1691-1703.
- DAVEY, F.J., HAMPTON, M., CHILDS, J., FISHER, M.A., LEWIS, K. & PETTINGA, J.R. (1986): Structure of a growing accretionary prism, Hikurangi margin, New Zealand. *Geology* **14**, 663-666.
- DAWSON, J.B. (1980): *Kimberlites and Their Xenoliths*. Springer-Verlag, Berlin.
- EHRENBERG, S.N. (1979): Garnetiferous inclusions in minette from the Navajo Field. In *The Mantle Sample: Inclusions in Kimberlite and Other Volcanics* (F.R. Boyd & H.O.A. Meyer, eds.). Amer. Geophys. Union, Washington, DC, 330-334.
- ENGLER, A.E.J., ITSON, S.P., ENGEL, C.G., STICKNEY, D.M. & CRAY, E.J., JR. (1974): Crustal evolution and global tectonics: a petrogenetic view. *Geol. Soc. Amer. Bull.* **85**, 843-858.
- ESPERANCA, S. & HOLLOWAY, J.R. (1986): The origin of the high-K latites from Camp Creek, Arizona: constraints from experiments with variable fO_2 and aH_2O . *Contr. Mineral. Petrology* **93**, 504-512.
- _____ & _____ (1987): On the origin of some mica lamprophyres: experimental evidence from a mafic minette. *Contr. Mineral. Petrology* **95**, 207-216.
- FLEET, A.J. (1984): Aqueous and sedimentary geochemistry of the rare earth elements. In *Rare Earth Element Geochemistry* (P. Henderson, ed.). *Developments in Geochemistry 2*, Elsevier Pub., New York, NY, 343-369.
- FRENZEL, G. (1971): Die mineral Paragenese der Albersweiler Lamprophyre (Sudpfalz). *Neues Jahrb. Mineral. Abh.* **115**, 164-191.
- FULLAGAR, P.D. (1971): Age and origin of plutonic intrusions in the Piedmont of the southeastern Appalachians. *Geol. Soc. Amer. Bull.* **82**, 2845-2862.
- _____ & BUTLER, J.R. (1979): 325 to 265 m.y. old granitic plutons in the Piedmont of the southeastern Appalachians. *Amer. J. Sci.* **279**, 161-185.
- GOLDSMITH, R., MILTON, D.F. & WILSON, F.A. (1978): Preliminary geologic map, geologic map index, and annotated bibliography, Charlotte 2° sheet, North Carolina and South Carolina. *U.S. Geol. Surv. Open-File Map* **78-590**.
- GUICHARD, F., CHURCH, T.M., TREUIL, M. & JAFFREZIC, H. (1979): Rare earths in barites: distribution and effects of aqueous partitioning. *Geochim. Cosmochim. Acta* **43**, 983-997.
- HOLE, M.J., SAUNDERS, A.D., MARRINER, G.F. & TARNEY, J. (1984): Subduction of pelagic sediments: implication for the origin of Ce-anomalous basalts from the Mariana Islands. *J. Geol. Soc. London* **141**, 453-472.
- HOWER, J., ESLINGER, E.V., HOWER, M.E. & PERRY, E.A. (1976): Mechanism of burial metamorphism of argillaceous sediments: 1: Mineralogical and chemical evidence. *Geol. Soc. Amer. Bull.* **78**, 725-737.
- HYNDMAN, D.W. (1985): *Petrology of Igneous and Metamorphic Rocks*. McGraw-Hill, New York, NY.
- JAHN, B., SUN, S.S. & NESBITT, R.W. (1979): REE distribution and petrogenesis of the Spanish Peaks igneous complex, Colorado. *Contr. Mineral. Petrology* **70**, 281-298.
- JAQUES, A.L. (1976): High-K₂O island-arc volcanic rocks from the Finisterre and Adelbert Ranges, northern Papua New Guinea. *Geol. Soc. Amer. Bull.* **87**, 861-867.
- KAY, R.W. (1980): Volcanic arc magmas: implications of a melting-mixing model for element recycling in the crust-upper mantle. *J. Geol.* **88**, 497-522.
- _____ (1984): Elemental abundances relevant to identification of magma sources. *Roy. Soc. London Philos. Trans. Ser. A* **310**, 535-547.

- KIRCHNER, J.G. (1979): Petrographic significance of a carbonate-rich lamprophyre from Squaw Creek, northern Black Hills, South Dakota. *Amer. Mineral.* **64**, 986-992.
- KRAMER, W. (1976): Geneses der Lamprophyre in Berich der Fichtelgebirgisch-Erzgebirgischen Antiklinalzone. *Chem. Erde* **35**, 1-49.
- KRAUSKOPF, K.B. (1979): *Introduction to Geochemistry (2nd ed.)*. McGraw Hill, New York, NY.
- LIPMAN, P.W. (1980): Cenozoic volcanism in the western United States: implications for continental tectonics. In *Continental Tectonics*, Nat. Acad. Sciences, Washington, DC, 161-174.
- LYONS, J.I., JR. & CLABAUGH, S.E. (1973): Pyroclastic and extrusive iron ore at Durango, Mexico. *Geol. Soc. Amer., Abstr. Prog.* **5**, 723.
- MASUDA, A., NAKAMURA, N. & TSUYOSHI, T. (1973): Fine structures of mutually normalized rare-earth patterns of chondrites. *Geochim. Cosmochim. Acta* **37**, 239-248.
- MCLENNAN, S.M., NANCE, W.B. & TAYLOR, S.R. (1980): Rare earth element - thorium correlations in sedimentary rocks and the composition of the continental crust. *Geochim. Cosmochim. Acta* **44**, 1833-1839.
- MCSWEEN, H.Y., COISH, R.A. & NORMAN, M.D. (1979): A discussion of the paper "Coexisting acid and basic melts; geochemistry of a composite dyke." *J. Geol.* **87**, 209-214.
- MERCIER, J.-C. (1979): Peridotite xenoliths and the dynamics of kimberlite intrusion. In *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics* (F.R. Boyd & H.O.A. Meyer, eds.). Amer. Geophys. Union, Washington, DC, 197-212.
- MEYER, H.O.A. (1976): Kimberlites of the continental United States: a review. *J. Geol.* **84**, 377-403.
- MIELKE, J.E. (1979): Composition of the Earth's crust and distribution of the elements. In *Reviews of Research on Modern Problems in Geochemistry* (F.R. Siegel, ed.). Int. Assoc. Geochem. Cosmochem. and UNESCO, Paris, 13-37.
- MOORE, G.F., SHIPLEY, T.H. & LONSDALE, P.F. (1986): Subduction erosion versus sediment offscraping at the tow of the Middle America Trench off Guatemala. *Tectonics* **5**, 513-523.
- MORRISON, G.W. (1980): Characteristics and tectonic setting of the shoshonite rock association. *Lithos* **13**, 97-108.
- NĚMEC, D. (1975): Petrochemie und Genese der Lamprophyrischen und Lamproiden Ganggesteine in Nordostteil der Bohmischen Masse (CSSR). *Z. Geol. Wiss. (Berlin)* **3**, 37-52.
- (1977): Differentiation of lamprophyre magma. *Krystalinikum* **13**, 73-87.
- PARK, C.F., JR. (1961): A magnetite "flow" in northern Chile. *Econ. Geol.* **56**, 431-436.
- PECCERILLO, A. (1985): Roman comagmatic province (central Italy): evidence for subduction-related magma genesis. *Geology* **13**, 103-106.
- PE-PIPER, G. (1984): Zoned pyroxenes from shoshonite lavas of Lesbos, Greece: inferences concerning shoshonite petrogeneses. *J. Petrology* **25**, 453-472.
- PHILPOTTS, A.R. (1967): Origin of certain iron-titanium oxide and apatite rocks. *Econ. Geol.* **62**, 303-315.
- PIPER, D.Z. (1974): Rare earth elements in the sedimentary cycle: a summary. *Chem. Geol.* **14**, 285-304.
- REED, J.C., JR., MARVIN, R.F. & MANGUM, H.H. (1970): K-Ar ages of lamprophyre dykes near Great Falls, Maryland-Virginia. *U.S. Geol. Surv. Prof. Pap.* **700-C**, C145-C149.
- REYMER, A. & SCHUBERT, G. (1984): Phanerozoic addition rates to the continental crust and crustal growth. *Tectonics* **3**, 63-77.
- ROCK, N.M.S. (1984): Nature and origin of calc-alkaline lamprophyres: minettes, vogesites, kersantites and spessartites. *Roy. Soc. Edinburgh Trans., Earth Sci.* **74**, 193-227.
- RODEN, M.F. (1981): Origin of coexisting minette and ultramafic breccia, Navajo Volcanic Field. *Contr. Mineral. Petrology* **77**, 195-206.
- ROGERS, N.W., BACHINSKI, S.W., HENDERSON, P. & PARRY, S.J. (1982): Origin of potash-rich basic lamprophyres: trace element data from Arizona minettes. *Earth Planet. Sci. Lett.* **57**, 305-312.
- ROSS, C.A. & ROSS, J.R. (1985): Carboniferous and early Permian biogeography. *Geology* **13**, 27-30.
- ROWELL, W.F. & EDGAR, A.D. (1983): Cenozoic potassium-rich mafic volcanism in the western U.S.A.: its relation to deep subduction. *J. Geol.* **91**, 338-341.
- SACKS, I.S. & SNOKE, J.A. (1984): Structure and evolution of the continental lithosphere. In *Physics and Chemistry of the Earth* (H.N. Pollack & V.R. Murthy, eds.). Pergamon Press, Oxford, U.K. and New York, N.Y., **15**, 3-37.
- SINHA, A.K. & ZIETZ, I. (1982): Geophysical and

- geochemical evidence for a Hercynian magmatic arc, Maryland to Georgia. *Geology* **10**, 593-596.
- SMITH, A.G., HURLEY, A.M. & BRIDEN, J.G. (1981): *Phanerozoic Paleocontinental World Maps*. Cambridge Univ. Press, London.
- THOMPSON, R.N., MORRISON, M.A., HENDRY, G.L. & PARRY, S.J. (1984): An assessment of the relative roles of crust and mantle in magma genesis: an elemental approach. *Roy. Soc. London Philos. Trans. Ser. A* **310**, 549-590.
- VOGEL, T.A. & WILBAND, J.T. (1978): Coexisting acidic and basic melts: geochemistry of a composite dyke. *J. Geol.* **86**, 353-371.
- VOLFINGER, M. (1976): Effect de la temperature sur les distributions de Na, Rb, et Cs entre la sanidine, la muscovite, la phlogopite et une solution hydrothermale sous une pression de 1 kbar. *Geochim. Cosmochim. Acta* **40**, 267-282.
- WASS, S.Y. (1979): Fractional crystallization in the mantle of late-stage kimberlitic liquids — evidence from xenoliths from the Kiama Area, N.S.W., Australia. In *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics* (F.R. Boyd & H.O.A. Meyer, eds.). Amer. Geophys. Union, Washington, DC, 366-373.
- _____ & ROGERS, N.W. (1980): Mantle metasomatism — precursor to continental alkaline volcanism. *Geochim. Cosmochim. Acta* **44**, 1811-1823.
- WEAVER, C.E. & BECK, K.C. (1971): Clay-water diagenesis during burial: how mud becomes gneiss. *Geol. Soc. Amer. Spec. Pap.* **134**.
- WESTBROOK, G.K., SMITH, M.J., PEACOCK, J.H. & POULTER, M.J. (1982): Extensive underthrusting of undeformed sediment beneath the accretionary complex of the Lesser Antillies subduction zone. *Nature* **300**, 625-628.
- ZARTMAN, R.E., BROCK, M.R., HEYL, A.V. & THOMAS, H.H. (1967): K-Ar and Rb-Sr ages of some alkalic intrusive rocks from central and eastern United States. *Amer. J. Sci.* **265**, 848-870.

Received February 18, 1987; revised manuscript accepted October 13, 1987.