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# THE FRACTIONATION EFFECT OF KAERSUTITE IN BASALTIC MAGMAS

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## Abstract

A banded alkali gabbro intrusion with layers alternately rich and poor in kaersutite is to be found at Brossard, Montreal. This differentiated series has yielded fractionation patterns in which P, Mn, Cu, Zn, Rb, Sr, Y, Th are strongly concentrated in the residual magma, and Cr, Ni, and Mg in the phenocryst phase. K shows no correlation with Rb and the ratio K/Rb ranges from about 380 in the probable parental rock to 1230 in the crystal concentrate. The remaining elements, Co, Al, Si, K, Ti, $Fe^{2+}$, Ca are distributed approximately equally between phenocryst and liquid.

## Introduction

Recent work on suites of lavas from oceanic islands carried out in this laboratory has confirmed that the range of composition of primary basaltic magmas is relatively limited. Fractionation of low pressure, high temperature mineral phases under near-surface conditions frequently greatly extends the compositional variation of the primary basalts or basanites.

Under conditions of apparently only slightly differing $P_{H_2O}$, or P (total) rather similar magmas may have a spinel, olivine, plagioclase or clinopyroxene as the primary phase appearing on the liquidus producing quite dissimilar fractionation trends. Nevertheless, study of the trace element fractionation patterns of olivine, clinopyroxene and plagioclase yields patterns so distinctive that it is possible to suggest a given magma is the residual product of, for example, olivine fractionation even though no olivine cumulate rocks are present.

Following on previous studies which showed some of the trace element patterns and distribution coefficients developed during fractionation subject to plagioclase control (Gunn & Watkins 1969), olivine control (Gunn 1971), ankaramitic (Op + Cpx) control (Gunn *et al.* 1970), and in partial melt series (Gunn & Mooser 1971), the present paper deals with the effects of fractionation by kaersutitic hornblende.

## GEOLOGICAL BACKGROUND

The Monteregian Province (Adams 1903) consists of a series of 14 principal alkaline intrusive (probably subvolcanic) complexes of Early Cretaceous age distributed linearly across southern Quebec. Each of the main centres is a complex of roughly elliptical intrusions, often concentrically arranged, with the main rock-types ranging from an olivine-kaersutite-pyroxenite (montrealite) to nepheline gabbro, yamaskite, lamprophyre, monzonite, syenite, nordmarkite, pulaskite, etc.

East of the Mount Royal complex at Brossard, excavation for the St. Lawrence seaway has exposed a body of banded kaersutite-bearing rock, possibly a buried extension of Mt. Royal, possibly a separate stock. It is at least a mile across and is similar in composition to the camptonite dikes of Mt. Royal. However, it should be noted that these are not true camptonites (which are accumulative in texture), but are rather olivine-free nepheline basalts which, crystallising under the conditions of high $P_{H_2O}$ common to all Monteregian magmas, have crystallised an amphibole as the primary ferromagnesian phase. Philpotts (1970) has presented geophysical evidence for the existence of a similar buried stock of Monteregian rock in the Port of Montreal some miles to the east.

## PETROGRAPHY

The rock is banded in layers up to 8 in. across. Samples are available only from excavated blocks due to flooding of the seaway, but banding in the Monteregian intrusions is commonly (but not always) vertical or nearly so. The layering is of an unusual type in that it consists of a wide range in proportion of coarse (1 cm) kaersutite phenocrysts and microcrystalline groundmass. Many hundreds of tons of excavated blocks all show continuous alternating rhythmic banding of this type, the "base" of bands having as high as 60% phenocrysts decreasing to as little as 5% at the "top".

The phenocrysts are euhedral with $X$ = pale yellow ; $Y$ = light brown ; $Z$ = reddish brown ; $Z \wedge c = 12°$ ; $2V\alpha = 60°$ (uncorrected).

Multiple electron probe analysis of grains show them to be highly homogeneous with the exception of a little iron enrichment at the extreme crystal margins (table 1). Rare grains of serpentinised olivine and diopsidic augite are the only other macroscopic phases. The groundmass is microcrystalline, often of the appearance of devitrified glass, but includes plentiful titanomagnetite, ragged kaersutite and clinopyroxene, rare red biotite, possible feldspar, and nepheline. The mafic nature of the groundmass is similar to that of nephelinites and limburgites associated with alkaline oceanic islands.

Some of the rock blocks contain plentiful 1cm ocelli of zeolite. Powder diffraction patterns have confirmed the presence of analcime and dolomite.

### *Chemical methods*

Whole rock analyses were made at about 2 in. intervals across a single rhythmic unit with compositions ranging from less than 5% kaersutite to more than 60% (Table 2). Mineral separates estimated at 97% purity were made by repeated passes through a magnetic separator. Further hand-picking under a binocular microscope removed grains with included foreign material but did not appreciably improve results. (Table 1).

Major and trace element determinations were made by *x*-ray fluorescence with the exception of sodium (done by atomic absorption) and P (colorimetry). The precision of replicate determinations varies from ± 0.3% $SiO_2$, to ± .002% MnO, ± 5 ppm Cr, ± 2.0 ppm Th, Pb, and ± 0.8 ppm Rb. All matrix corrections, correlation coefficients and data plotting are accomplished by computer.

## RESULTS

Amphiboles are "carpet bag" minerals in that, for the major components the weight concentration of the oxides is little different from the

TABLE 1. MICROPROBE ANALYSIS OF KAERSUTITE, BROSSARD SEAWAY

| | | |
|---|---|---|
| $SiO_2$ | 41.6 | (41.4–41.7) |
| $Al_2O_3$ | 13.6 | (13.4–14.0) |
| $TiO_2$ | 3.8 | ( 3.7– 4.0) |
| FeO | 9.2 | ( 8.5–10.3) |
| MgO | 15.5 | (15.2–16.0) |
| CaO | 11.5 | (10.6–12.5) |
| $Na_2O$ | 2.8 | ( 2.5– 3.1) |
| $K_2O$ | 1.9 | ( 1.6– 2.2) |
| MnO | 0.1 | |
| $P_2O_5$ | 0.0 | |
| | 100.0 | |

Average of 20 random points in phenocryst kaersutite. Maximum range encountered is given with the high FeO, low MgO points being located on extreme crystal margins. These margins show no significant differences when compared with groundmass kaersutite.

Total iron is given as FeO.

TABLE 2. MONTREGIAN KAERSUTITE, SEAWAY, BROSSARD, ANALYSES SUMMED TO 100% WATER-FREE

| NUMBER | MT0001 | MT2001 | MT3001 | MT0002 | MT2002 | MT0003 | MT0004 | MT0005 | MT2005 | MT0008 | MT0009 | MT0006 | MT0007 | NUMBER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SIO2 | 40.36 | 40.33 | 40.36 | 40.41 | 40.41 | 40.25 | 40.48 | 40.56 | 40.75 | 41.42 | 40.94 | 40.33 | 39.79 | SIO2 |
| AL2O3 | 12.90 | 12.80 | 12.90 | 13.19 | 13.19 | 13.10 | 13.36 | 13.23 | 13.19 | 13.96 | 13.94 | 13.35 | 13.03 | AL2O3 |
| TIO2 | 4.31 | 4.32 | 4.31 | 4.26 | 4.26 | 4.28 | 4.20 | 4.19 | 4.18 | 4.10 | 4.09 | 4.21 | 4.20 | TIO2 |
| FE2O3 | 7.23 | 7.40 | 7.23 | 6.36 | 6.36 | 5.87 | 5.46 | 5.61 | 5.61 | 2.62 | 9.48 | 6.21 | 5.35 | FE2O3 |
| ~~FEO~~ | ~~6.59~~ | ~~6.59~~ | ~~6.59~~ | ~~6.66~~ | ~~6.66~~ | 6.79 | 6.47 | 6.36 | 6.36 | 6.17 | ~~0.00~~ | ~~6.39~~ | ~~6.80~~ | FEO |
| MNO | .17 | .18 | .17 | .17 | .17 | .17 | .14 | .14 | .14 | .08 | .07 | .16 | .15 | MNO |
| MGO | 8.25 | 8.07 | 8.25 | 8.91 | 8.91 | 9.85 | 10.87 | 10.94 | 10.83 | 14.95 | 15.01 | 10.49 | 10.69 | MGO |
| CAO | 13.75 | 13.84 | 13.75 | 13.69 | 13.69 | 13.64 | 13.20 | 13.20 | 13.18 | 12.43 | 12.20 | 13.02 | 13.45 | CAO |
| NA2O | 3.52 | 3.54 | 3.52 | 3.52 | 3.52 | 3.31 | 3.15 | 3.10 | 3.08 | 2.20 | 2.18 | 3.37 | 3.80 | NA2O |
| K2O | 2.02 | 2.03 | 2.02 | 2.04 | 2.04 | 2.10 | 2.16 | 2.18 | 2.18 | 2.02 | 2.02 | 1.88 | 2.24 | K2O |
| ~~P2O5~~ | ~~.90~~ | ~~.90~~ | ~~.90~~ | ~~.79~~ | ~~.79~~ | .65 | .51 | .49 | .49 | .07 | ~~.07~~ | ~~.59~~ | ~~.49~~ | P2O5 |
| H2O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | H2O |
|  | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ |  |
| TOTAL | 100.001 | 100.000 | 100.001 | 99.999 | 99.999 | 100.000 | 100.001 | 100.001 | 100.002 | 100.001 | 99.999 | 99.999 | 99.999 | TOTAL |
| CR | 66.4 | 68.5 | 68.6 | 92.7 | 95.3 | 146.1 | 171.7 | 174.8 | 176.1 | 358.0 | -0.0 | 157.9 | 158.0 | CR |
| ~~NI~~ | 52.8 | 52.5 | 52.9 | 65.1 | 66.1 | 84.3 | 101.6 | 107.1 | 105.2 | 190.9 | -0.0 | 91.0 | 96.2 | NI |
| CU | 135.5 | 136.1 | 135.5 | 120.8 | 122.2 | 110.5 | 95.8 | 88.5 | 89.1 | 20.6 | -0.0 | 103.5 | 71.2 | CU |
| ZN | 99.7 | 100.0 | 98.6 | 95.8 | 98.9 | 84.4 | 75.9 | 71.4 | 70.7 | 39.9 | -0.0 | 82.9 | 72.4 | ZN |
| GA | 18.7 | 18.3 | 16.2 | 16.5 | 16.1 | 17.0 | 15.0 | 16.2 | 15.3 | 13.4 | -0.0 | 15.9 | 16.5 | GA |
| RB | 45.1 | 43.6 | 43.8 | 41.7 | 42.1 | 39.5 | 36.2 | 36.2 | 36.4 | 13.6 | -0.0 | 32.0 | 38.3 | RB |
| SR | 1049.3 | 1054.0 | 1051.4 | 1055.0 | 1062.6 | 948.2 | 889.6 | 856.8 | 860.3 | 538.0 | -0.0 | 1017.3 | 844.3 | SR |
| ~~BA~~ | ~~658.3~~ | ~~667.4~~ | ~~677.3~~ | ~~671.5~~ | ~~688.7~~ | 567.2 | 562.6 | 507.9 | 517.9 | 400.4 | ~~-0.0~~ | ~~502.2~~ | ~~458.7~~ | BA |
| PB | .4 | 3.8 | 5.2 | 2.4 | 3.5 | 2.3 | 2.3 | .8 | 3.5 | 35.3 | -0.0 | 3.4 | 3.7 | PB |
| TH | 7.9 | 11.4 | 8.1 | 8.5 | 6.2 | 8.7 | 4.2 | 2.5 | 6.2 | 1.0 | -0.0 | 7.9 | 5.3 | TH |
| CO | 60.2 | 63.5 | 62.6 | 61.4 | 61.5 | 62.0 | 62.8 | 63.2 | 64.8 | 68.0 | -0.0 | 62.9 | 59.4 | CO |
| Y | 10.2 | 10.0 | 9.9 | 9.3 | 9.1 | 8.9 | 7.3 | 7.4 | 7.5 | 4.4 | -0.0 | 8.2 | 7.4 | Y |
| AL/TI | 3.00 | 2.96 | 3.00 | 3.09 | 3.09 | 3.06 | 3.18 | 3.16 | 3.16 | 3.41 | 3.41 | 3.17 | 3.10 | AL/TI |
| CA/NA | 3.903 | 3.907 | 3.903 | 3.891 | 3.891 | 4.119 | 4.190 | 4.257 | 4.272 | 5.658 | 5.587 | 3.862 | 3.535 | CA/NA |
| K/NA | .573 | .573 | .573 | .579 | .579 | .635 | .686 | .704 | .708 | .918 | .924 | .557 | .590 | K/NA |
| CA/SR | 131 | 131 | 131 | 130 | 129 | 144 | 148 | 154 | 153 | 231 |  | 128 | 159 | CA/SR |
| K/RB | 372 | 386 | 383 | 405 | 402 | 442 | 496 | 500 | 498 | 1230 |  | 487 | 486 | K/RB |
| ~~MG/NI~~ | ~~1298~~ | ~~1277~~ | ~~1296~~ | ~~1136~~ | 1119 | 970 | 889 | 848 | 855 | 650 |  | ~~957~~ | ~~923~~ | MG/NI |

MT0001 BASALT,KAERSUTITE,APHYRIC. SEAWAY CANAL, BROSSARD, MONTREAL.
MT2001 BASALT,KAERSUTITE. DUPLICATE MAJOR AND TRACE ELEMENT ANALYSIS OF MT001.
MT3001 BASALT,KAERSUTITE. DUPLICATE TRACE ELEMENT ANALYSIS OF MT001.
~~MT0002 BASALT,KAERSUTITE. 10-15PC KAERSUTITE,SEAWAY CANAL,BROSSARD,~~ MONTREAL.
MT2002 BASALT,KAERSUTITE. DUPLICATE TRACE ELEMENT ANALYSIS OF MT002.
MT0003 BASALT,KAERSUTITE. 15-30PC KAERSUTITE,SEAWAY CANAL,BROSSARD, MONTREAL.
MT0004 BASALT,KAERSUTITE. 30-50PC KAERSUTITE,SEAWAY CANAL,BROSSARD, MONTREAL.
MT0005 BASALT,KAERSUTITE. 50-60PC KAERSUTITE,SEAWAY CANAL,BROSSARD, MONTREAL.
MT2005 BASALT,KAERSUTITE. DUPLICATE MAJOR AND TRACE ELEMENT ANALYSIS OF MT0005.
~~MT0008 KAERSUTITE. 95 PERCENT PURE. XRF ANAL. SEPARATED FROM MT0005.~~
MT0009 KAERSUTITE. 97 PERCENT PURE. MAJOR EL. XRF ANALYSIS ONLY, BROSSARD.
MT0006 BASALT,KAERSUTITE,APPROX. 30PC KAERSUTITE WITH ZEOLITE OCELLI,BROSSARD
MT0007 BASALT,KAERSUTITE,APPROX. 30PC KAERSUTITE WITH APPROX. 50PC ZEOLITE.

rock in which they occur, that is, the distribution coefficients are close to unity. Amphiboles from undersaturated or oversaturated magmas are usually themselves under or oversaturated, and the norms of the Brossard kaersutites show a marked degree of undersaturation.

Kaersutites analysed from yamaskite, gabbro and essexite at Mt. Yamaska, another of the Monteregian Hills, are considerably less magnesian and rather richer in $TiO_2$ compared with the Brossard amphibole (Gandhi 1970) ; while those of Mt. Shefford are similar in most components but have only half the $K_2O$ (Frisch 1970). Xenolithic kaersutites from the Canary Is. are again rather less magnesian and of lower $K_2O$ content, (Borley *et al.* 1971) as are kaersutites of Japan (Aoki 1970).

The matrix of the Brossard rocks is similar in composition to the aphyric "camptonite" dikes of the Mt. Royal complex. This coupled with the lack

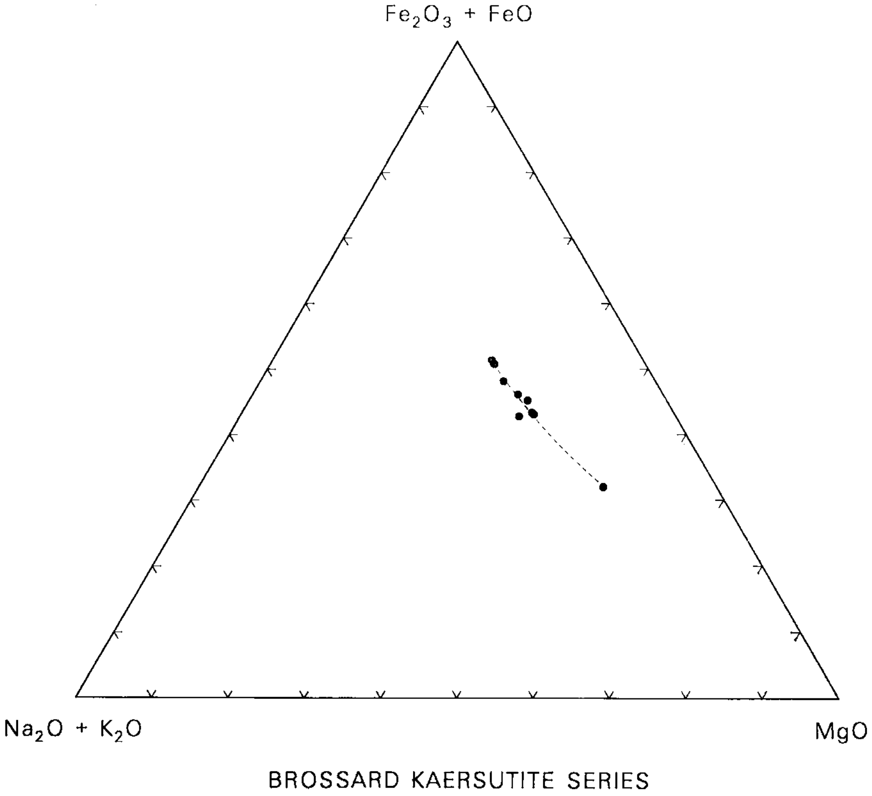

FIG. 1. F.M.A. diagram of Brossard series. Note the characteristic slope of the points which project towards the MgO-alkalies axis.

of zoning in the crystals shown by microprobe scans and the small magnitude of the difference in composition of both phenocryst and groundmass kaersutite shown by the same method, suggests that a rock with less than 10% phenocryst kaersutite represents the parental liquid. From this we can make some estimates of the distribution coefficients for a range of elements.

The elements analysed can be grouped into :

(a) Active elements, which enter the phenocryst phase in greater proportion than that in the liquid, *i.e.* those with distribution coefficients $k >> 1$;

(b) Passive elements with distribution coefficients $k \sim 1$;

(c) Residual elements markedly discriminated against by the phenocryst phase, with $k << 1$.

The high Na and K contents of the kaersutite yield a distinctive F.M.A. diagram (Fig. 1).

The distribution coefficients for a number of elements are given in Table 3. The higher values, *e.g.* for Cr and Ni are subject to some uncertainty due to uncertainty as to the exact composition of the initial liquid.

The series described here have characteristics which may enable kaersutite control to be recognized even in residual magmas :

(a) the marked enrichment of Rb relative to K in the residual liquids distinguishes the series from other series controlled by olivine +

TABLE 3. DISTRIBUTION COEFFICIENTS (KAERSUTITE/LIQUID) FOR THE BROSSARD SERIES. Significant distribution coefficients for olivine for the 1959 Kilauea Iki series have been added in parentheses.

| A | | B | | | C | | |
|---|---|---|---|---|---|---|---|
| Active Elements | | Passive Elements | | | Residual Elements | | |
| Cr = 5–6.0 | | Co | 1.1 | (3.0) | Sr | 0.5 | |
| Ni = 3–4.0 | (10.0) | Al | 1.08 | | Mn | 0.5 | (1.0 ) |
| Mg = 1.8 | ( 4.5) | Si | 1.0 | | Zn | 0.43 | ( .95) |
| | | K | 1.0 | | Y | 0.43 | |
| | | Ti | 0.95 | | $Fe^{3+}$ | 0.36 | |
| | | $Fe^{3+}$ | 0.94 | | Rb | 0.3 | |
| | | Ca | 0.90 | | Cu | 0.16 | |
| | | P | 0.80 | | | | |
| | | Ga | 0.65 | | | | |
| | | $\Sigma Fe^{3+}$ | 0.7 | (1.1) | Th. | < .1 | |
| | | Na | 0.6 | | | | |
| | | Ba | 0.6 | | | | |

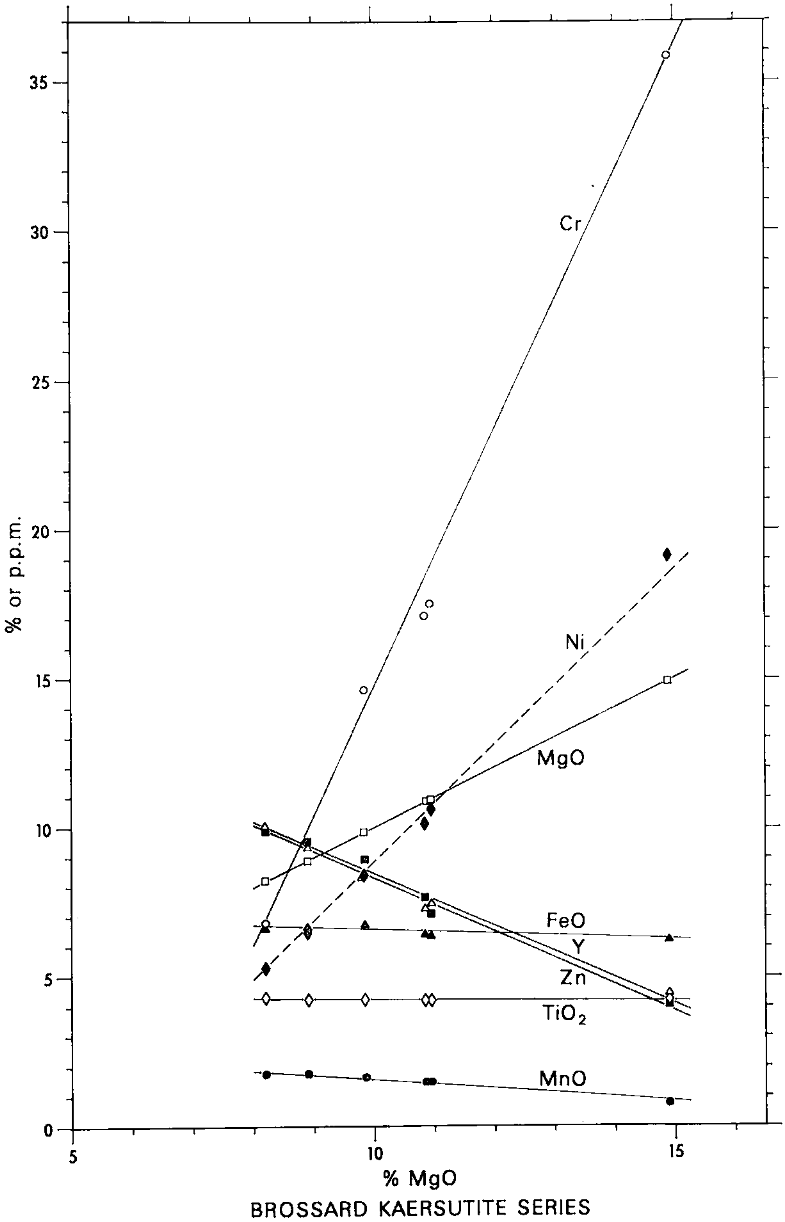

FIG. 2. Distribution of Cr, Ni, MgO, FeO, Y, Zn, $TiO_2$, MnO *vs.* MgO for the Brossard Series. Points on the extreme right are of pure kaersutite. Co (not shown) is present in almost constant amount at 63 ± 5 ppm.

spinel or Ol + Cpx + Sp fractionation. The constant K content (distribution coefficient $k = 1.0$) contrasts strongly with plagioclase-controlled series where $k$ may be lower than 0.1 (Gunn & Watkins 1970).

(b) the slope of the Cr *vs.* Mg distribution is only half that of alkali basalts subject to ankaramitic (Ol + Cpx + Sp) control as seen in the Crozet Is. (Gunn *et al.* 1970) and in the Cape Verde and Azores Is. (unpublished data) and in oceanite series. Thus at an MgO content of 15% we have a Mg/Cr of 250 compared with 170 for typical ankaramitic series (Gunn *et al.* 1970) and 113 for olivine controlled series (Gunn 1971). Similarly the Mg/Ni = 470 compared with 210 and 160 at the same MgO content. The Ni content is however somewhat lower throughout than many other series

(c) the large number of distribution coefficients with values near unity, e.g. for Al, Si, Ti, Ca, as well as K, are all specific.

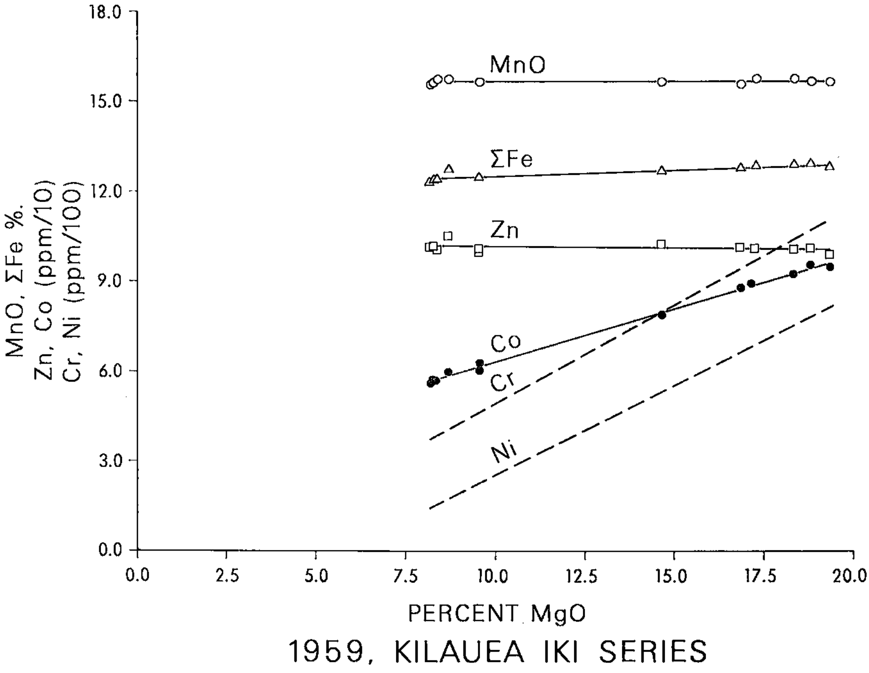

Fig. 3. Distribution of ferromagnesian elements in an olivine controlled series (1959 Kilauea Iki lavas), mean slopes of Cr and Ni added from separate diagram; data from Gunn (1971). Compare with figure 2.

(d) Manganese and ferrous iron show unusually strong relative fractionation with FeO/MnO ranging from 31 to 77. Gallium is also somewhat enriched in the residual liquid relative to Al as in Zn relative to Fe. Ferric iron is also strongly residual unlike $Fe^{3+}$.

Philpotts & Schnetzler (1970) found kaersutite/matrix distribution coefficients of 0.43 for Rb, 0.55 for Sr and 0.42 for Ba for a Mount Royal camptonite. This rock had a K/Rb of 325 in the matrix and 1060 in the kaersutite, while the Brossard rock had K/Rb of about 380 in the probable parental rock and 1230 in the amphibole. Such high K/Rb ratios appear typical of all hornblendes (Hart & Aldrich 1967; Griffin *et al.* 1967). Of 33 amphiboles listed by the former writers from a wide range of rock

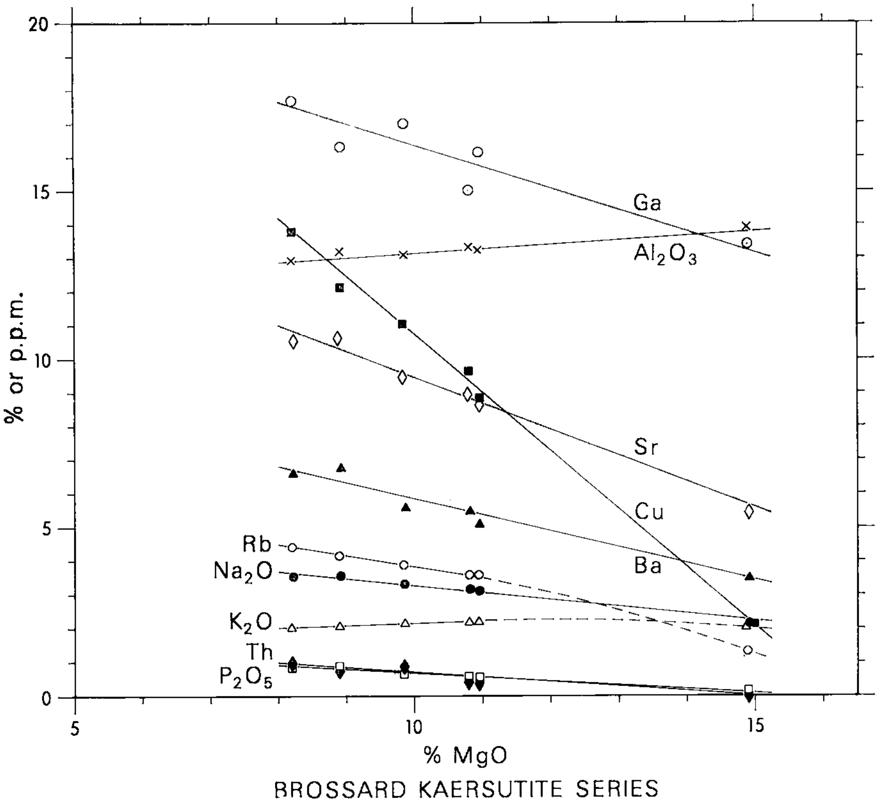

FIG. 4. Distribution of Ga, $Al_2O_3$, Cu, Sr, Ba, Rb, $Na_2O$, $K_2O$, Th, $P_2O_5$ with MgO in the Brossard series. Note curvature of trends of K and Rb suggesting some loss of these elements from the system.

types, only 7 have K/Rb less than 500 and these amphiboles are mainly from granites and pegmatites.

## SUMMARY

The residual liquid of an alkali-basalt magma fractionated by kaersutite removal would be somewhat impoverished in Cr, Ni and Mg, and would be enriched in Th, Rb, P, Cu and to a lesser degree, in Zn, Y, Mn, Sr, Ba, Na, $\Sigma Fe^{3+}$ and Ga. Certain hornblende pegmatites occurring within the ultrabasic kaersutite-bearing olivine pyroxinites of Mount Royal have the appropriate compositions.

The Rb, Sr, P, etc. enrichment is of interest when considering the genesis of syenites and trachytes, but kaersutite crystallisation must be accompanied by pyroxene to accomplish the necessary iron, magnesium and calcium removal. In the alkali-gabbro suites of Mt. Royal and of Tahiti (McBirney & Aoki 1970), trachytes and syenite occur in close association with ultramafic masses, plainly accumulative in origin, of just such pyroxene-kaersutite rocks. Removal of typical pyroxene-kaersutite "Montrealite" from an alkali gabbro magma yields a monzonite-syenite residual series (Woussen 1970).

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