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THE BLACKBURN CARBONATITES, NEAR OTTAWA, ONTARIO: DYKES WITH FLUIDIZED EMPLACEMENT

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ABSTRACT

Four narrow, Cretaceous, carbonatite dykes cut Middle Ordovician limestone in two adjacent quarries near Ottawa (Ontario). P, F, Cl, Ba, Sr, Zn, Y, *REE*, Nb, Ta, U, Th and Zr are all present in high concentrations and are within the carbonatite range. Light rare-earths are strongly enriched (La/Yb between 120 and 180). Dykes contain the following minerals, in order of decreasing abundance: dolomite, calcite, fluorapatite, phlogopite, hematite, kaolinite, pyrite. Other minerals are present in amounts less than 1%. Dolomite, fluorapatite, phlogopite, zircon and pyrochlore were precipitated from a carbonatite magma at depth; the magma was transported rapidly as fluidized particles, which were introduced in fractures in the limestone. Apatite + phlogopite equilibrated at 600°C. Carbonate + K-feldspar + phlogopite equilibrated at a total pressure in excess of 2 kbar, and the assemblage was transported rapidly toward the surface. Many Precambrian and Paleozoic xenoliths were incorporated during upward migration. Calcite was derived mainly from the wallrock. This model is consistent with the abundance of xenoliths (30–60% by weight), rounded and fragmented crystals, an incompatible association of minerals, dolomite–quartz and calcite–phlogopite assemblages, deeply striated contacts, oriented mushroom-shaped cavities, and virtual absence of alteration in the wallrock. Kaolinized xenoliths may be samples from near the underlying Paleozoic–Precambrian unconformity.

Keywords: carbonatite, fluidization, cerium, strontium, fluorine, xenoliths, kaolinization, dolomite, fluorapatite, pyrochlore, Ottawa, Ontario.

SOMMAIRE

Quatre dykes étroits de carbonatite, d'âge crétacé, recoupent le calcaire ordovicien moyen dans deux carrières situées près d'Ottawa (Ontario). Les éléments P, F, Cl, Ba, Sr, Zn, Y, les terres rares, Nb, Ta, U, Th et Zr s'y trouvent tous en concentrations élevées et typiques des carbonatites. Les terres rares légères sont fortement enrichies (La/Yb entre 120 et 180). Les dykes contiennent les minéraux suivants, présentés en ordre décroissant de leur abondance: dolomite, calcite, fluorapatite, phlogopite, hématite, kaolinite, pyrite. Les autres phases représentent moins de 1%. Dolomite, fluorapatite, phlogopite, zircon et pyrochlore ont été précipités d'un magma carbonatitique encore à grande profondeur; ce magma a ensuite été transporté sous forme de particules fluidisées, qui ont été introduites dans les fissures du calcaire. Apatite et phlogopite ont atteint l'équilibre à 600°C. L'assemblage carbonate + feldspath potassique + phlogopite a atteint l'équilibre à une pression supérieure à 2 kbar et a par la suite été transporté rapidement vers la surface. Plusieurs enclaves d'âge précambrien et paléozoïque ont été incorporées pendant la mise en place. La calcite a surtout été dérivée des roches encaissantes. Ce modèle concorde avec l'abondance des enclaves (de 30 à 60% en poids), l'allure arrondie et fragmentée des cristaux, une association de minéraux incompatibles, les assemblages dolomite–quartz et calcite–phlogopite, les rayures profondes le long des contacts, les cavités orientées en forme de champignon, et la quasi-absence de phénomènes d'altération dans les roches encaissantes. Des enclaves kaolinisées pourraient provenir de la non-conformité entre la section paléozoïque et le socle précambrien.

(Traduit par la Rédaction)

Mots-clés: carbonatite, fluidisation, cerium, strontium, fluor, enclaves, kaolinisation, dolomite, fluorapatite, pyrochlore, Ottawa, Ontario.

INTRODUCTION

Carbonatite dykes, exposed in two active limestone quarries at Blackburn Hamlet, east of Ottawa (Fig. 1), have been given passing notice only. Cursory field and laboratory examinations were made by K.L. Currie in 1964-65 and by D.D. Hogarth in 1969-70, and their findings are summarized in a regional guidebook (Baird 1972, the "Francon dikes"). In the meantime, mention was made of these same dykes by Gittins (1966 the "Eastview dikes"). These rocks, referred to as the "Blackburn carbonatites", were also the subject of three B.Sc. theses (Hon 1970, Rushforth 1985, Curran 1986) and two recent GAC–MAC–CGU excursion guidebooks (Hogarth & Rushforth 1986, Williams & Telford 1986). Despite the accessibility of this locality, no complete account of these rocks has appeared in the geological literature. The present paper summarizes

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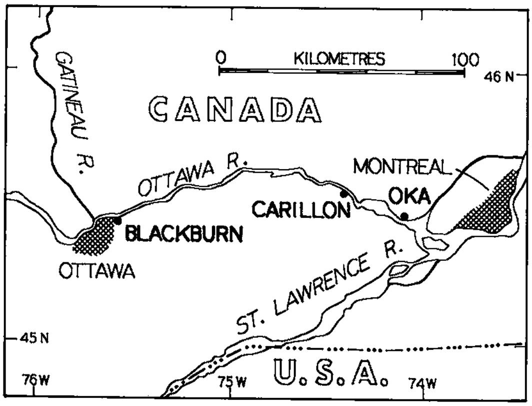

FIG. 1. Location map.

existing data, presents new information, and discusses the origin of these rocks. Isotopic data will be reserved for a future paper.

GEOLOGY

General setting

The Paleozoic geology of the Blackburn (Francon) quarries has been described by Williams & Telford (1986) and the following paragraphs have been summarized from their work.

The northern quarry of Francon Ltd. exposes 35 m of flat-lying limestone (biomicrite) of the Gull River and Bobcageon formations of the Middle Ordovician Ottawa Group, that can be correlated with Pamelia, Lowville, Chaumont and Napanee formations of New York State. Strata in the uppermost part of the Gull River Formation, containing fragmented *Tetradium*, separate it from the overlying Bobcageon Formation.

Between the two quarries, an east–west fault has a downward displacement of 25 m on its southern side. A wedge of Gull River limestone has been uplifted between branches of this fault.

The south quarry exposes about 55 m of flat-lying

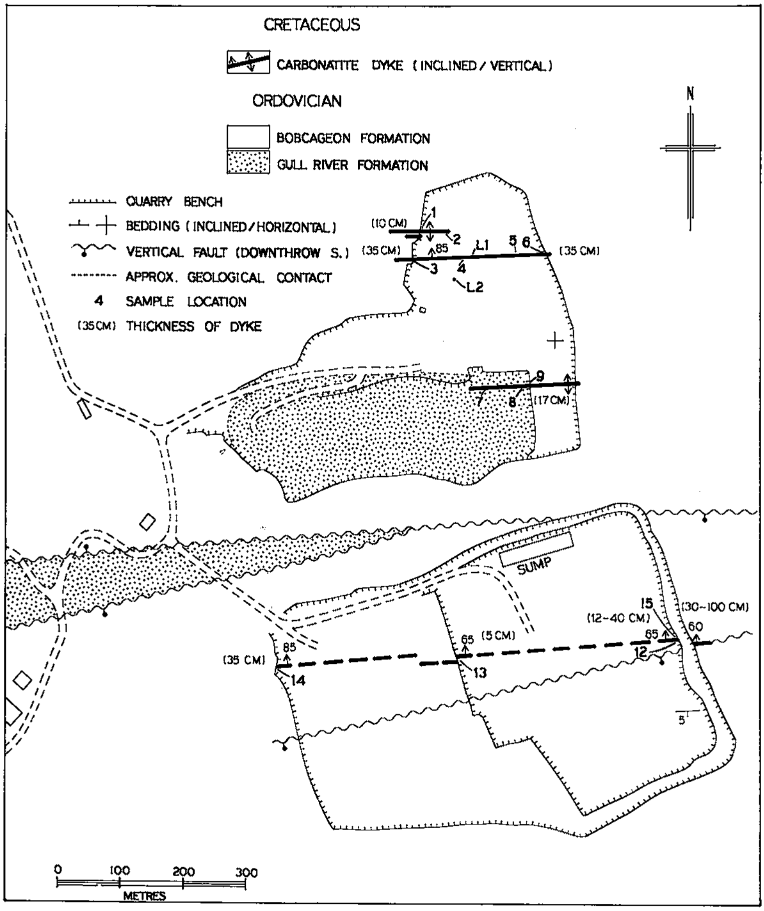

FIG. 2. Geology of the Francon quarries, Blackburn Hamlet, Ontario.

TABLE 1. FISSION TRACK AGES OF APATITES

No.	T_s	T_i	ρ_s	ρ_i	Ma
1	716	605	$1.22 \cdot 10^5$	$5.88 \cdot 10^4$	115.2 ± 7.2
7	725	428	$1.15 \cdot 10^5$	$6.195 \cdot 10^4$	103.1 ± 7.0
CB 15-1	1020	655	$1.476 \cdot 10^5$	$7.426 \cdot 10^4$	110.6 ± 6.5

T_s = Number of fossil tracks counted, T_i = Number of neutron-induced tracks counted, ρ_s = Number of fossil tracks/cm^2, ρ_i = Number of neutron-induced tracks/cm^2. Samples 1 and 7 are from the north and south dykes, north quarry, Blackburn, Ontario; sample CB 15-1 is from the west dyke, Carillon Dam, Ontario.

Bobcageon biomicritic limestone, the upper 30 m of which are characterized by black chert nodules. These strata are equivalent to the Napanee and Kings Falls formations of New York State.

Into this flat-lying sequence were intruded four steeply inclined to vertical carbonatite dykes, three in the north and one in the south quarry. These dykes run parallel to the fault and to a well developed set of joints. The dykes are typically compact and yellowish grey or green. Local variants are white, compact "porcellanite" (a 30-cm layer in the hanging wall, east exposure, south quarry) and blue granular carbonatite (central exposure, south quarry). The dykes are generally less than 1 m thick. Quarry outlines, geology, representative dyke thicknesses, and sample locations are shown in Figure 2.

The limestone changes from light grey or green to grey-black within a few centimeters of contact with the dykes. In some places minor recrystallization has taken place, and pieces of wallrock have become detached and rafted into the interior of the dykes. However, at the contact and within Ordovician xenoliths, fossils retain their identity and there is little evidence of metamorphic reactions.

Age of dykes

Shafiqullah (1971), used the constants $\lambda_\epsilon = 0.585 \times 10^{-10}$ yr^{-1}, $\lambda = 5.30 \times 10^{-10}$, $K^{40}/K = 0.0119$ (atomic) to obtain the following K–Ar ages in one of the Blackburn dykes: (i) phlogopite, 10.15% K_2O, 190 ± 10 Ma; (ii) phlogopite, 7.99% K_2O, 299 ± 16 Ma; and (iii) whole rock 0.21% K_2O, 321 Ma. He concluded that the age discrepancies were due "either to small Precambrian granitic inclusions or the presence of excess argon in one of the mica varieties". He therefore favored a younger age and suggested that the dykes belong to the Monteregian (Cretaceous) cycle of intrusion.

The tentative Cretaceous age was tested with fission-track dating. Apatite concentrates were annealed at 390–410°C for two hours to destroy fossil fission tracks, and then irradiated with thermal neutrons in the nuclear reactor at McMaster University. The neutron flux was measured with N.B.S. dosimeter glass 962a and the age was given by the equation $T = 6.45 \cdot 10^9 \ln (1 + 4.30 \cdot 10^{-8} \rho_d \cdot \rho_s/\rho_i)$, where T is the age (years), and ρ_d, ρ_s and ρ_i are, respectively, the fission-track density (tracks/cm^2) in the dosimeter glass, in the original mineral, and in the mineral after annealing and irradiating with neutrons.

Fission-track data are summarized in Table 1. Data from two samples of the Blackburn dykes are tabulated with those of a sample from a dyke at Carillon, Ontario. The Carillon carbonatites have been described by Crépeau (1963) and Williams (1984). The age of carbonatites at each locality is about 110 Ma. This is almost the same as the Rb–Sr age (109 Ma) of the Oka carbonatite but somewhat younger than the fission-track age at Oka (125–132 Ma; Gold *et al.* 1986). The new ages extend the Cretaceous Monteregian intrusive activity 110 km westward from the Oka Complex.

CHEMICAL COMPOSITION

Analytical methods

Rock specimens listed in Table 2 were analyzed as lithium borate glasses by X-ray fluorescence (XRF) using a rhodium tube. Concentrations of rare-earth elements were determined by direct current plasma-atomic emission spectrophotometry (DCP). Precision estimates and further data on methodology are given by Hogarth *et al.* (1985). Concentrations of S, F, and Cl in specimens 1, 4, 7, L1, and L2 were determined by ion exchange chromatography (relative uncertainty of the amount present: 4% F and Cl, 2% S). Concentrations of Ta, U and Th were determined by neutron activation (INAA) at Ecole Polytechnique, Montreal (expected precision 20% Ta in L1 and L2, 10% Th and U in L1 and L2, other determinations 5% of the amount present). Rocks in Table 3 were analyzed by atomic-absorption spectrophotometry (AAS) (relative uncertainty: 5% CaO and MgO, 7% FeO_T and Sr, 20% Ba).

TABLE 2. WHOLE-ROCK COMPOSITIONS OF CARBONATITE, LIMESTONE AND MARBLE

	1	4	7	12	13	14	15	L1	L2	M1	AC
wt.%											
P_2O_5	3.29	2.55	3.22	1.76	1.69	1.14	0.01	0.01	0.01	0.01	1.73
SiO_2	2.37	4.61	1.80	2.25	1.31	2.06	0.32	7.01	5.29	4.19	5.67
TiO_2	0.25	0.67	0.08	0.14	0.14	0.11	0.01	0.08	0.06	0.12	0.30
Al_2O_3	1.64	1.93	1.12	1.37	1.31	0.82	0.04	1.86	1.65	0.46	1.77
FeO_T	4.21	5.99	4.34	1.80	3.03	2.13	1.54	0.76	0.86	0.31	7.20
MnO	0.27	0.31	0.43	0.36	0.29	0.42	0.09	0.03	0.03	0.03	0.78
MgO	10.37	9.84	13.70	2.16	3.23	9.86	19.00	1.38	1.26	6.26	6.10
CaO	36.12	33.38	32.50	46.15	45.72	38.96	31.91	47.30	48.00	41.82	37.06
Na_2O	0.00	0.00	0.04	0.00	0.00	0.00	0.08	0.06	0.00	0.00	1.09
K_2O	0.07	0.55	0.13	0.06	0.00	0.06	0.02	0.76	0.60	0.22	0.87
S_T ppm	7300	2375	9925	1400	3000	2500	600	3150	4425	100	3600
F	2500	2650	2900	—	—	—	—	550	500	—	3800
Cl	300	550	250	—	—	—	—	<100	<100	—	3100
Ba	360	510	220	370	620	290	90	40	55	230	2800
Sr	2870	1680	3300	1730	2200	2080	250	480	465	370	6300
Zr	380	380	280	340	290	240	140	40	30	10	320
Y	70	70	90	40	50	40	<10	10	20	<10	110
Nb	150	270	190	170	230	125	<10	—	—	—	290
Ta	—	10.0	12.9	9.7	7.7	—	—	0.19	0.12	—	13.0
Zn	50	80	120	50	<10	50	55	<10	<10	40	270
Ni	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	10
Cr	20	20	<10	<10	<10	<10	10	<10	<10	<10	18
Rb	<10	20	10	<10	<10	<10	<10	20	10	10	52
U	—	3.1	8.7	24	7.1	—	—	1.60	0.76	—	—
Th	—	31.0	42.0	54	39.0	—	—	1.41	1.14	—	—
La ppm	238	252	375	314	400	351	2.9	8.50	9.44	4.69	960
Ce	488	528	785	585	745	646	6.4	23.5	24.8	5.84	1309
Nd	192	183	280	240	291	250	3.35	8.72	9.50	2.64	459
Sm	[30]	[28]	[40]	40.8	49.0	41.2	0.9	[1.8]	[2.1]	[0.6]	71.5
Eu	8.4	7.88	11.0	15.5	16.7	11.9	[0.3]	0.55	0.70	[0.2]	17.0
Gd	20.8	18.2	26.0	[30]	[36]	[24]	[0.9]	1.58	1.68	[0.6]	46.7
Dy	[12.6]	[11.8]	[13.8]	11.9	17.2	10.75	[0.8]	[1.7]	[1.6]	[0.6]	28.0
Er	3.65	3.73	4.78	3.4	5.0	3.55	0.35	0.88	0.75	0.30	10.1
Yb	2.05	2.18	2.83	[1.7]	[2.5]	[2.1]	0.3	0.85	0.70	[0.25]	6.5
∑REE	1000	1035	1540	1240	1560	1340	16	48	51	16	2910
La/Yb	120	120	130	180	160	170	10	10	13	19	150

Analyses: 1, 4, 7, 12, 13, 14, 15, L1, L2 Blackburn Quarry; M1 diopside-calcite marble, Cantley, Quebec; AC average carbonatite, Ba, Sr, Zr, Nb, Ta, Zn, Ni, Cr, REE from Samoylov (1984), other elements from Gold (1966). Square brackets indicate interpolated or extrapolated values.

Minerals were analyzed with an electron microprobe (EM; Cambridge Geoscan Mk5), operated at 15 kV with a specimen current of 50 nA. Special standards were benitoite (Ba), tugtupite and syn. chlorapatite (Cl), nat. phlogopite and nat. fluorapatite (F), rare-earth glasses (La, Ce, Pr, Nd), syn. lueshite (Nb), tantalum metal (Ta), syn. brannerite (U), zircon (Zr). Data were reduced with the EMPADR program of Rucklidge & Gasparrini (1969).

Bulk-rock composition

In Table 2 we present the chemical composition of a typical specimen from each dyke of the north quarry (anal. 1, 4, 7) and typical dyke rock from each of the three exposures in the south quarry (anal. 12, 13, 14). For comparison, we also show the composition of limestone in the north quarry (anal. L1, L2), calcite–diopside–phlogopite marble from the Cantley district, Quebec (anal. M1), "porcellanite", south quarry (anal. 15), and average carbonatite [column AC; Ba, Sr, Zr, Nb, Ta, Zn, Ni, Cr, *REE* from Samoylov (1984); other elements from Gold (1966), "typical abundance"].

TABLE 3. ATOMIC ABSORPTION DATA FOR CARBONATITE AND LIMESTONE FROM THE NORTH QUARRY

Sample	Rock type	MgO(wt.%)	FeO_T(wt.%)	Sr(ppm)	Ba(ppm)
1	North dyke	10.23	4.95	3060	350
2	"" ""	11.29	6.15	2960	480
3	Middle dyke	10.02	7.03	1620	470
4	"" ""	8.19	6.63	1605	390
5	"" ""	8.83	6.51	2190	450
6	"" ""	9.23	6.67	2420	350
7	South dyke	14.85	4.93	3540	300
8	"" ""	13.62	3.99	3450	355
9	"" ""	13.96	4.27	3530	270
L1	Limestone	1.45	0.86	530	40
L2	""	1.44	1.00	520	—

The abundances of certain minor and trace elements in the Blackburn dykes (*viz.* P, F, Cl, Ba, Sr, Zr, Y, Nb, Ta, Zr, U, Th; anal. 1–14, Table 2) bear a close resemblance to those in carbonatite (*cf.* column AC, Table 2), but are very different from those of limestone and marble (anal. L1, L2, M1). Niobium is an important discriminant because it is virtually absent in all limestones and most marbles. Rankama (1948) gave a range of 0.3 to 0.55 (av. 0.35) ppm for three biogenic sediments, comprising limestone and chalk, and 0.035 to 0.05 (av. 0.04) ppm for three marbles. In contrast, specimens of the Blackburn dykes contain 125–270 ppm Nb, *i.e.* concentrations 400 to 800 times the limestone background. These values fall within the range of carbonatite given by Samoylov (1984), *viz.* 7–2790 ppm Nb (av. 290 ppm Nb, 790 bulk compositions considered).

Similarly, the concentrations of Ta, U and Th are much higher in the Blackburn dykes (av. 10.1, 10.7 and 42.5 ppm, respectively) than in the wall-rocks (0.2, 1.2 and 1.3 ppm, respectively; Table 2) and in limestone in general [*e.g.*, Upper Jurassic limestone from southern Germany, with 0.2, 0.8 and 1.3 ppm, respectively; Parekh *et al.* (1977)]. The Ta concentration of the dykes (av. 10.1 ppm) approaches the mean (13.0 ppm) of 740 determinations from world-wide carbonatites (Samoylov 1984); U and Th lie within the range of values from five carbonatite complexes (Gold 1966; 0.55–54.6 and 0–2375 ppm, respectively).

REE patterns also are suggestive of carbonatites. The high *REE* content ($\Sigma REE > 1000$ ppm) and strong *LREE* enrichment (La/Yb > 100) are characteristic of carbonatites but different from limestone and marble (Table 2; Fig. 3). Abundances of *REE* in AC were averaged from data of Samoylov (1984) according to locality (31 localities listed, embracing 572 analyses).

TABLE 4. NORMS (WEIGHT PERCENT) OF CARBONATITE SAMPLES FROM THE NORTH QUARRY

	1	4	7
dolomite	48.5	40.1	59.7
calcite	29.9	31.6	17.5
apatite	7.9	6.1	7.7
phlogopite	0.8	6.1	5
hematite	3.5	5.7	2.8
kaolinite	4.1	2.8	1.1
pyrite	1.4	0.4	1.9
quartz	0.2	0.9	0.0
rutile	0.2	0.6	0.1
fluorite	0.1	0.0	0.1
pyrochlore	0.03	0.06	0.04
zircon	0.08	0.08	0.06
microcline	<0.1	0.0	< 0.5
plagioclase	0.0	0.0	< 0.1
chlorite	0.0	< 0.1	< 0.1
garnet	0.0	< 0.1	0.0
Total	96.7	94.4	96

< indicates mineral observed in thin section but not apparent in the norm.

The data in Table 2 reveal differences in the composition of individual dykes, a suspicion that is strengthened by additional data for rocks from the north quarry (Table 3). The south dyke (samples 7,

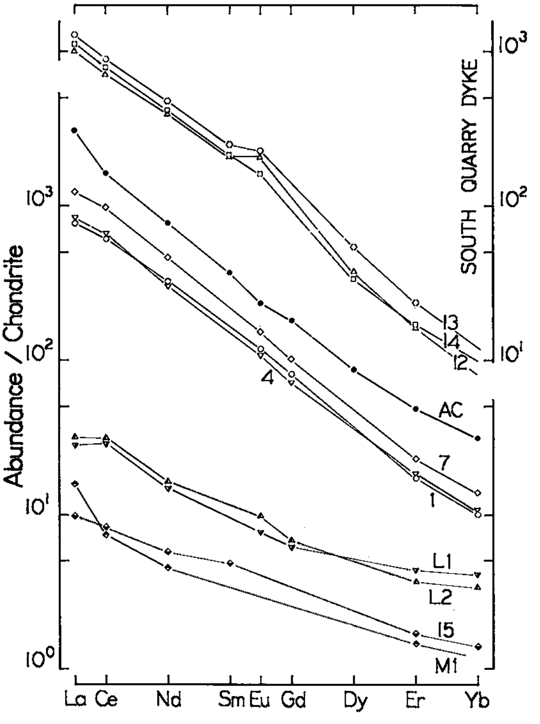

FIG. 3. Chondrite-normalized *REE* abundances of the Blackburn dykes (1, 4, 7, 12, 13, 14), associated limestone (L1, L2), "porcellanite" (15), Gatineau marble (M1), and average carbonatite (AC). Note that the upper right vertical scale pertains to analyses from the south-quarry dyke, and the lower left vertical scale pertains to the other analyses. Samples are normalized against the chondrite values of Boynton (1984).

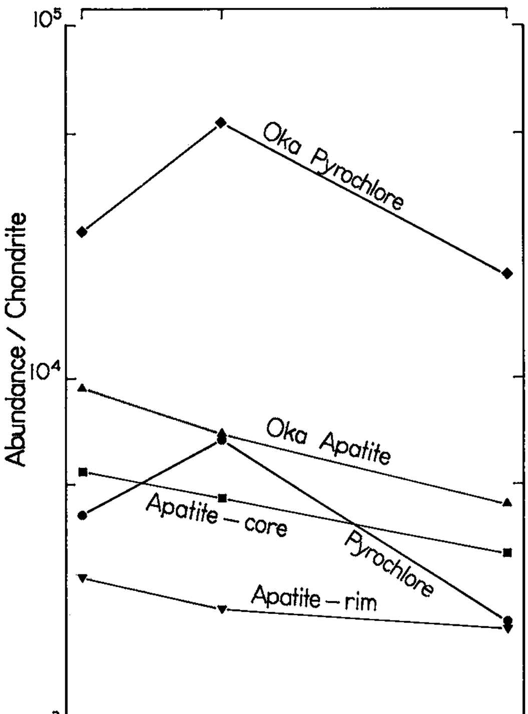

FIG. 4. Distribution of La, Ce and Nd in pyrochlore and apatite in the Blackburn dykes (three lower curves) and Oka carbonatite (two upper curves; data from Eby 1975, number OL-7).

8, 9) is relatively rich in Mg and Sr but poor in Fe, the middle dyke (samples 3, 4, 5, 6) is relatively rich in Fe but poor in Mg and Sr, and the northern dyke (samples 1, 2) has an intermediate composition. Barium is lowest in the south dyke.

As shown by data in Table 2, limestone at the contact of the middle dyke (L1) has a composition almost identical with that of limestone 35 m to the south (L2), indicating that there has been negligible migration of elements from the carbonatite into the wallrock.

The carbonatite from the south quarry is similar to that of the north quarry but contains higher Mg and lower Ca, reflecting less dolomite and more calcite. Phosphorus (1.53% P_2O_5) is half as abundant in carbonatite from the north quarry, yet Ce, chiefly contained in apatite in the south quarry, is equally common at the two localities (av. 630 ± 30 ppm for each set of 3 analyses). Zirconium is 16% and Nb 14% less in carbonatite of the south quarry.

"Porcellanite" of the south quarry is composed of spherulitic dolomite with irregular accumulations of quartz. The rock has a composition (Table 2, anal. 15) very different from that of carbonatite (especially low *REE*, Sr, Nb and P).

MINERALOGY OF CARBONATITE, NORTH QUARRY

Mineral abundances are listed in Table 4. Because the rock is fine-grained, we calculated the norms (wt.%) from whole-rock data (Table 2). Minerals (all identified in concentrates or from thin sections), were given compositions derived from electron-microprobe analysis and these compositions were used in normative calculations. Abundances were calculated in the following order (critical components in parentheses): pyrite (S), pyrochlore (Nb_2O_5), apatite (P_2O_5), phlogopite (K_2O), fluorite (F), kaolinite (Al_2O_3), hematite (Fe_2O_3), zircon (ZrO_2), quartz (SiO_2), rutile (TiO_2), dolomite (MgO), calcite (CaO). Observed minerals that do not appear in the norm (microcline, plagioclase, chlorite, garnet) were given estimated abundances.

When compared with thin-section observations, the first seven minerals listed in Table 4 appear to be in the correct order of abundance. Modal minerals

TABLE 5. ELECTRON-MICROPROBE DATA ON PYROCHLORE, PHLOGOPITE AND APATITE FROM THE NORTH QUARRY

Pyrochlore	(4)	Phlogopite cores	b(4)	c(1)	d(1)	Apatite	x[r](5)	x[c](5)	y(6)	z[r](2)	z[c](2)
TiO_2	2.88	SiO_2	39.88	39.75	39.57	P_2O	41.66	41.64	41.61	41.10	42.71
ZrO_2	0.27	TiO_2	1.22	0.75	3.74	SiO_2	0.00	0.00	0.01	0.99	0.01
Nb_2O_5	65.97	Al_2O_3	13.03	12.23	15.11	La_2O_3	0.10	0.20	0.09	0.08	0.07
Ta_2O_5	0.43	FeO_T	5.90	11.12	4.42	Ce_2O_3	0.21	0.43	0.18	0.18	0.16
U_3O_8	0.03	MnO	0.11	0.20	0.08	Pr_2O_3	0.05	0.12	0.00	0.02	0.02
La_2O_3	0.15	MgO	24.95	21.05	22.67	Nd_2O_3	0.13	0.22	0.04	0.05	0.05
Ce_2O_3	0.64	CaO	0.00	0.01	0.00	MnO	0.11	0.11	0.09	0.03	0.04
Pr_2O_3	0.06	BaO	0.34	0.23	0.11	CaO	53.27	53.23	54.37	55.40	55.60
Nd_2O_3	0.14	Na_2O	1.26	0.89	0.72	SrO	0.68	1.13	0.63	0.28	0.56
FeO_T	0.23	K_2O	8.61	8.92	9.40	Na_2O	0.23	0.30	0.31	0.41	0.33
MnO	0.04	F	0.96	3.01	2.97	F	2.36	2.26	2.42	1.62	2.64
SrO	1.05	Cl	0.00	0.00	0.00	Cl	0.01	0.01	0.04	0.05	0.01
BaO	0.00	H_2O*	3.73	2.66	2.84	H_2O*	0.64	0.69	0.60	1.01	0.55
CaO	16.17	Total	99.59	99.55	101.38	Total	98.46	99.39	100.39	100.54	101.64
Na_2O	7.02										
F	4.44										
H_2O*	0.31										
Total	97.96										
Ions per 16 B		Ions per 44 charges				Ions per 6 Z					
Ti	1.075	Si	5.708	5.840	5.588	P	6.000	6.000	5.998	5.834	5.998
Zr	0.065	Al	2.198	2.118	2.412	Si	0.000	0.000	0.002	0.166	0.002
Nb	14.802	Fe	0.094	0.042	0.000		6.	6.	6.	6.	6.
Ta	0.058		8.	8.	8.						
	16.										
U	0.003	Al	0.000	0.000	0.103	La	0.006	0.013	0.006	0.005	0.004
La	0.027	Ti	0.131	0.083	0.397	Ce	0.013	0.027	0.011	0.011	0.010
Ce	0.116	Fe	0.612	1.324	0.522	Pr	0.003	0.007	0.000	0.001	0.001
Pr	0.011	Mn	0.013	0.025	0.010	Nd	0.008	0.013	0.004	0.003	0.003
Nd	0.025	Mg	5.324	4.609	4.773	Mn	0.016	0.016	0.013	0.004	0.006
Fe	0.095		6.08	6.04	5.80	Ca	9.710	9.707	9.919	9.952	9.882
Mn	0.017					Sr	0.067	0.112	0.062	0.027	0.054
Sr	0.302	Ba	0.019	0.013	0.006	Na	0.076	0.099	0.102	0.133	0.106
Ba	0.000	Ca	0.000	0.002	0.000		9.90	9.99	10.12	10.14	10.07
Ca	8.598	Na	0.350	0.254	0.198						
Na	6.755	K	1.572	1.672	1.694						
	15.95		1.94	1.94	1.90						
						Cl	0.003	0.003	0.012	0.014	0.003
F	6.969	F	0.435	1.396	1.326	F	1.270	1.217	1.303	0.859	1.385
OH	1.031	Cl	0.000	0.000	0.000	OH	0.727	0.780	0.685	1.127	0.612
	8.	OH	3.565	2.604	2.674		2.	2.	2.	2.	2.
			4.	4.	4.						

All analyses represent the north dyke (sample 1), except y and z which are from the south and middle dykes, respectively (specimens 7 and 4). Numbers in parentheses indicate numbers of analyses averaged, asterisks indicate calculate values. Totals include subtracted oxygen equivalents. r indicates crystal rim, c indicates crystal core.

present in "trace amounts" that are not listed in Table 4 are: alkali amphibole (north dyke), scapolite (middle dyke), diopside (middle dyke) and two unidentified minerals (north dyke, north quarry). Shafiqullah (1971) also reported magnetite and aegirine from an unspecified dyke in the north quarry.

Pyrochlore

Pyrochlore was identified from the north and south dykes as pale yellow, rounded octahedra. Some grains are fragmented. The chemical composition (Table 5) agrees with that of pyrochlore from intermediate to late (dolomitic) stages of carbonatite evolution (Kapustin 1980): high Nb/Ta (*ca.* 130), low U (*ca.* 0.03%), low Zr (*ca.* 0.2%), high F/OH (*ca.* 0.7). *LREE* enrichment (Ce *ca.* 0.55%, Sm and Y undetectable by microprobe). The positive Ce anomaly (Fig. 4) is common in carbonatitic pyrochlore, as noted first by Semenov (1958). Lanthanum is approximately equal to Nd, thus extending the range of Nd/La below the limit of 1.5 proposed by Borodin & Barinskii (1961) for carbonatitic pyrochlore.

Apatite

Apatite occurs in all dykes as short prismatic to rounded and commonly fractured grains (some obviously fragmented). A few fractured grains have an overgrowth that predates fracturing as this overgrowth appears on part of the fragments only. Some grains show re-entrants against carbonate.

Chemically, the mineral is a zoned Sr-bearing fluorapatite containing a small to moderate amount of *REE* (Ce_2O_3 0.15 to 0.5%) with *LREE* enrichment (Sm, Yb undetectable by microprobe) and a weak negative Ce anomaly (Fig. 4). The additional charge due to *REE* substitution for Ca is compensated by a monovalent cation, in the coupled substitution scheme $2\ Ca^{2+} \rightarrow REE^{3+} + Na^{+}$. The Sr/Mn ratio averages 8.4. This is within the range of apatite from carbonatite, world-wide (1–250), and well above the ratio in apatite from gneiss and granite (0.2), as reported by Brasseur *et al.* (1962).

The average composition of five zoned crystals (*REE*, Sr-rich core) from the north dyke and six crystals from the south dyke are presented in Table 5 (anal. x and y, respectively). Crystals from the south dyke yield the following unit cell, and physical and chemical data: a = 9.388(1), c = 6.882(1) Å; D_{meas} = 3.28 g/cm^3; ϵ = 1.634, ω = 1.637; K_c = 0.1965, K_p = 0.194, compatibility index (Mandarino 1981) = 0.013. The last value is in the "superior category" of Mandarino, which suggests that our apatite compositions are correct.

A well defined overgrowth of highly birefringent apatite (B = 0.007; Fig. 5) was observed on apatite with normal birefringence (B = 0.003) in crystals

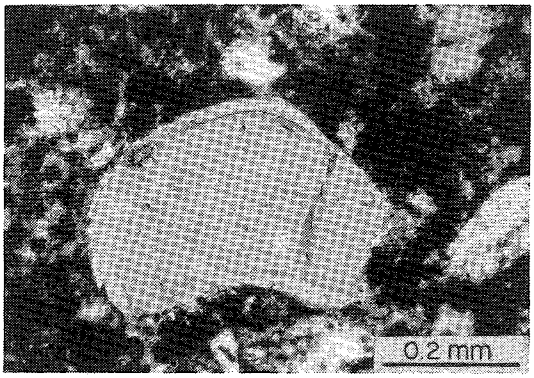

FIG. 5. Apatite with a more highly birefringent overgrowth of apatite enriched in Si, Na and possibly C. Middle dyke, north quarry; crossed polars.

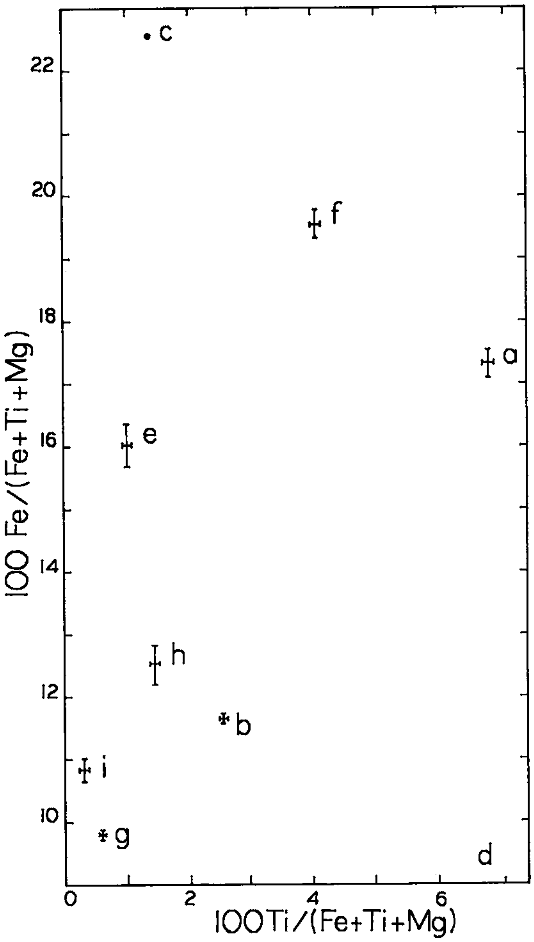

FIG. 6. 100 Fe/(Fe + Ti + Mg) *versus* 100 Ti/(Fe + Ti + Mg) (at.%) showing the composition of phlogopite from the three dykes of the north quarry.

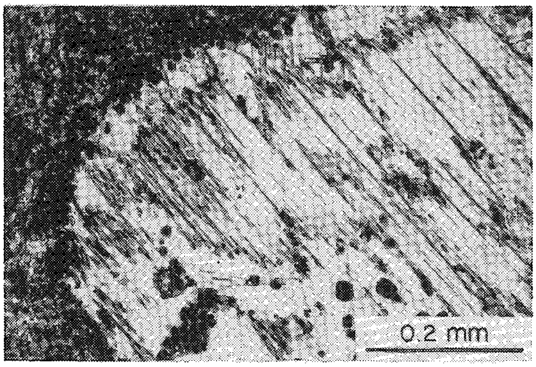

FIG. 7. Phlogopite crystal replaced along the edges and cleavage by calcite. North dyke, north quarry; plane-polarized light.

from the middle dyke, north quarry. The rims are enriched in Si and Na, but depleted in F and Sr. Analyses of one of these grains is given in Table 5, specimen z. The charge balance in the rim cannot be explained by conventional means; possibly part of the F site is left vacant (instead of filling with OH, as shown in Table 5).

Phlogopite

The most striking features of phlogopite from the Blackburn dykes are the variations in color and chemical composition in neighboring grains. Thus, within a single thin section ("Phlogopite cores", Table 5), some grains are deeply colored (*e.g.*, d), whereas others are comparatively pale (*e.g.*, c). These colors are correlated with Fe and Ti as noted by Deer *et al.* (1962, p. 49). The atomic variation of Fe and Ti in the cores of 8 grains from three different thin sections is shown graphically in Figure 6.

Pleochroism also varies. Specimens with $Al_2O_3 >$ 14 wt.% have a normal pleochroic scheme, with Z reddish to umber brown, X pale yellow brown to green, and an absorption formula $Z > X$ (*e.g.*, sample d, Table 5); those with $Al_2O_3 <$ 14 wt.% have a reverse pleochroic scheme, with X brown, Z very pale green, and an absorption formula $X > Z$ (*e.g.*, samples b and c, Table 5). This type of absorption is related to a low total of ^{IV}Al and Si ions and the accommodation of Fe^{3+} in tetrahedral sites (Grum-Grzhimailo & Rimskaya-Korsakova 1964, Hogarth *et al.* 1970).

In addition, some grains in the same thin section show different zonal characteristics: some have a darker rim than core, some are unzoned, and others have a darker core than rim. Clearly these color varieties reflect different T-P-X conditions during formation and provide evidence for disequilibrium.

The phlogopite is low in iron ($FeO_T <$ 10 wt.%) and, with the exception of two grains showing a sharply defined overgrowth from specimen 7, nearly all grains of phlogopite and apatite contain more fluorine in the rim than in the core (apatite 3–18% more, phlogopite 23–40% more). High-iron phlogopite (specimen c, Table 5) has a F-depleted rim.

Crystals of phlogopite are commonly bent and exfoliated. Some are partly replaced along cleavages and edges by calcite (Fig. 7).

Dolomite

The principal minerals of the dykes are dolomite with subordinate calcite (Table 6). The carbonates are commonly fine-grained and spherulitic; some spheroids consist entirely of dolomite, and others consist of dolomite cored with calcite in optical continuity (Fig. 8). A fine-grained aggregate of intermixed dolomite, calcite and hematite makes up the interstitial material. Calcite-cored spherules are absent in our polished thin sections, but two clean, rounded crystals of dolomite have the composition shown in Table 6. Notable is a small, but constant, Sr content (as apparent from Sr imaging). Attempts to analyze the interstitial dolomite proved unsuccessful, but it seems that, in all three dykes, this variety has a composition similar to that of the spheroidal dolomite in the north dyke (*i.e.*, 0.5–0.6 % SrO).

Calcite

Calcite is present in several forms, most of which are represented in Table 6. Calcite is characterized by low Mg (0.2 to 0.7% MgO) in all specimens except calcite f from a veinlet. The latter cuts dolomite, apatite, phlogopite, pyrochlore, and the other varieties of calcite. Strontium also is low in calcite (<0.1% SrO) and well below the content characteristic of carbonatitic calcite [*e.g.*, 0.61, 0.71% SrO, average of calcite from early and late carbonatites, respectively,

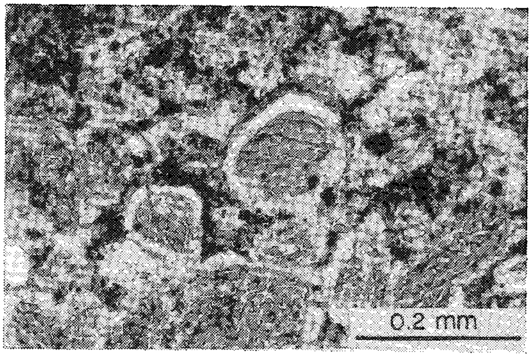

FIG. 8. Spheroidal texture of carbonates. The core of each grain consists of calcite (stained dark with alizarin). The white rim is dolomite. The matrix consists of dolomite, iron oxides, and some calcite. North dyke, north quarry; plane-polarized light.

TABLE 6. ELECTRON-MICROPROBE DATA ON CARBONATES FROM THE NORTH QUARRY

	Dolomite	Calcite					
	a(2)	b(3)	c(3)	d(4)	e(3)	f(2)	g(2)
CO_2*	46.46	43.63	43.18	44.75	43.74	44.65	44.46
FeO_T	0.63	0.08	0.31	0.03	0.19	0.06	0.01
MnO	0.46	0.06	0.09	0.03	0.07	0.06	0.04
MgO	19.39	0.63	0.24	0.71	0.22	1.21	0.60
CaO	31.03	54.61	54.37	55.97	55.18	55.12	55.78
SrO	0.64	0.00	0.00	0.03	0.08	0.00	0.00
Total	98.61	99.01	98.19	101.52	99.48	101.10	100.89
Ions per 12 charges							
C	2.	2.	2.	2.	2.	2.	2.
Fe	0.017	0.002	0.009	0.001	0.005	0.002	0.000
Mn	0.012	0.002	0.003	0.001	0.002	0.002	0.001
Mg	0.911	0.032	0.012	0.035	0.011	0.059	0.029
∑	0.94						
Ca	1.048	1.965	1.976	1.963	1.980	1.938	1.969
Sr	0.012	0.000	0.000	0.001	0.002	0.000	0.000
∑	1.06	2.	2.	2.	2.	2.	2.

Locations: a spheroidal crystal, specimen 1; b megacryst, specimen 1; c megacryst, specimen 4; d, megacryst specimen 7; e pseudomorph, specimen 1; f vein, specimen 1; g, limestone xenolith, specimen 7. Numbers in parentheses indicate numbers of analyses averaged, asterisks indicate calculated values.

according to Kapustin (1982)]. Note that the carbonatite calcite, represented by analyses b, c, d, e, is compositionally similar to xenolithic limestone calcite, analysis g.

Some calcite fills obvious cavities. In some cases the filled cavities are mushroom-shaped with the mushroom top pointing upward in the dyke (Fig. 9).

Feldspars, kaolinite and quartz

Feldspars were observed in thin sections from all occurrences. Analyses (Table 7) are from specimen 7 (south dyke, north quarry). Plagioclase with almost no calcium (analysis n) is present as an isolated, euhedral, unaltered and unzoned grain, with a two-component albite twin. In composition, freshness and twinning, it is similar to plagioclase from Precambrian fenites and carbonatites 20 km northwest (Hogarth & Lapointe 1984, Hogarth *et al.* 1985). In contrast, somewhat sericitized and complexly twinned calcic albite (p, q) coexists in a xenolith with coarse-grained microcline (m) as perthite, associated with quartz, in another part of the same polished thin section. The plagioclase rim (q) is slightly more sodic than the core (p). Plagioclase of this composition in perthite characterizes most granite pegmatites in the Precambrian terrane immediately north of the Ottawa River (Hogarth 1981). Around some xenoliths, a thin rim of green phlogopite separates microcline from dolomite (Fig. 10). Some xenoliths in the middle dyke (not analyzed)

TABLE 7. ELECTRON MICROPROBE DATA ON MICROCLINE, PLAGIOCLASE AND KAOLINITE FROM THE NORTH QUARRY

	Microcline	Plagioclase		
	m(3)	n(2)	p(2)	q(2)
SiO_2	64.18	68.64	66.28	67.41
Al_2O_3	18.23	19.36	20.90	19.92
Fe_2O_{3T}	0.07	0.03	0.03	0.03
BaO	0.25	0.00	0.03	0.02
CaO	0.08	0.06	1.50	0.70
Na_2O	0.54	11.78	11.04	11.51
K_2O	15.86	0.12	0.16	0.12
Total	99.21	99.99	99.94	99.71
Ions per 64 charges				
Si	11.976	11.997	11.656	11.848
Al	4.009	3.987	4.332	4.127
Fe^3	0.009	0.004	0.004	0.004
∑	15.99	15.99	15.99	15.98
Ba	0.018	0.000	0.002	0.001
Ca	0.016	0.010	0.283	0.131
Na	0.197	3.991	3.764	3.922
K	3.775	0.026	0.036	0.026
∑	4.01	4.03	4.08	4.08
Molecular percent				
Cs	0.5	0.0	0.1	0.0
Ab	4.9	99.1	92.2	96.2
An	0.4	0.3	6.9	3.2
Or	94.2	0.6	0.9	0.6

	Kaolinite		
	r(2)	s(1)	t(1)
SiO_2	44.24	43.19	44.31
TiO_2	——	0.01	0.03
Al_2O_3	37.83	33.11	38.98
Fe_2O_{3T}	0.01	2.13	0.08
MnO	——	0.00	0.00
MgO	0.00	0.73	0.08
CaO	0.14	0.18	0.20
BaO	0.00	0.00	0.00
Na_2O	0.00	0.00	0.06
K_2O	0.01	0.51	0.10
H_2O_C	13.32	12.76	13.55
H_2O_ε	4.45	7.38	2.61
Ions per 28 charges			
Si	3.982	4.060	3.923
Ti	——	0.001	0.002
Al	4.013	3.668	4.067
Fe^3	0.001	0.151	0.005
Mn	——	0.000	0.000
Mg	0.000	0.102	0.011
∑	4.01	3.92	4.08
Ca	0.013	0.018	0.019
Ba	0.000	0.000	0.000
Na	0.000	0.000	0.010
K	0.001	0.061	0.011
∑	0.01	0.08	0.04
Layer charge			
	0.03	0.10	0.06

H_2O_C = calculated H_2O for 8 OH in the formula, H_2O_ε = excess H_2O or H_2O_T (from deficit in total) - H_2O_C. Numbers in parentheses indicate number of analyses averaged. Location of analyses: m, n, p, q, r south dyke (specimen 7); s middle dyke (specimen 4); t north dyke (specimen 1).

FIG. 9. Mushroom-shaped cavities filled with calcite (central part of photograph) with the mushroom top pointing upwards in the dyke. The white, cigar-shaped areas are plucked grains, thought to represent the location of former apatite crystals. The surrounding matrix is mainly fine-grained dolomite. South dyke, north quarry; plane-polarized light.

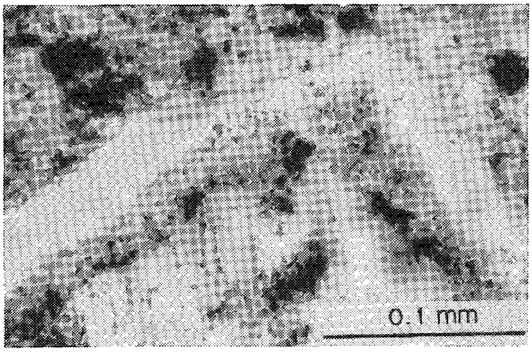

FIG. 10. A reaction between alkali feldspar (lower part of the photograph) and dolomite (main mineral, upper part of photograph) produced a rim of phlogopite (almost white) and a second rim of calcite below (mottled grey). South dyke, north quarry; plane-polarized light.

contain microcline but the largest xenolith in our collection (7 × 4 cm) had coarse-grained orthoclase ($2V_x$ = *ca.* 30°), similar to feldspar xenoliths found in Precambrian marble near Old Chelsea, Quebec, 20 km west-northwest of the Blackburn dykes (unpubl. data).

Kaolinite is common in all three dykes of the north quarry, as well as in the dyke of the south quarry. Compositions are given in Table 7. The kaolinite generally occurs as fine-grained aggregates, but in specimen 1 (analysis t) it was found as rectangular grains, with length-slow orientation, low birefringence and subparallel extinction, within a fine-grained mixture of fluorite and phlogopite. The low totals may be due to "excess" H_2O (as shown as H_2O_ϵ in Table 7) and, at least partly, to the influence of grain size on the X-ray emission of Al and Si. X-ray-diffraction data indicate 7 Å *c*-periodicity.

Quartz is present in three forms: strained xenolithic quartz, unstrained xenolithic quartz, and chalcedony. The strained quartz represents xenoliths of Precambrian granite pegmatite and biotite (± garnet) gneiss. Unstrained quartz was seen in the middle dyke, north quarry, as a quartz-cemented aggregate of well-sized quartz grains, some with an overgrowth of secondary quartz petrographically identical with Nepean sandstone, a Cambro-Ordovician formation at the base of the Paleozoic sequence in the Ottawa area (Williams & Telford 1986). No reaction between quartz and dolomite was observed in any of our thin sections.

Relative proportions of xenoliths and carbonatite

The profusion of obvious xenoliths has been noted by every investigator. However, it is difficult to distinguish xenocrysts from phenocrysts, and secondary from primary matrix. If we assume that the primary dyke material was dolomite (containing Sr and Mg) and apatite (containing Sr but no Mg), we may calculate the composition of primary dyke rock from the normative proportions of dolomite and apatite in the rock (Table 4) and the amount of Sr and Mg in the minerals (from electron-microprobe analyses). Furthermore, if we also assume that the present dyke composition is the result of mixing primary dyke material with limestone, we may deduce the proportion of primary and secondary fractions. Figure 11 shows the Sr–Mg relationships. In this manner, we have calculated that, in the north quarry, the south

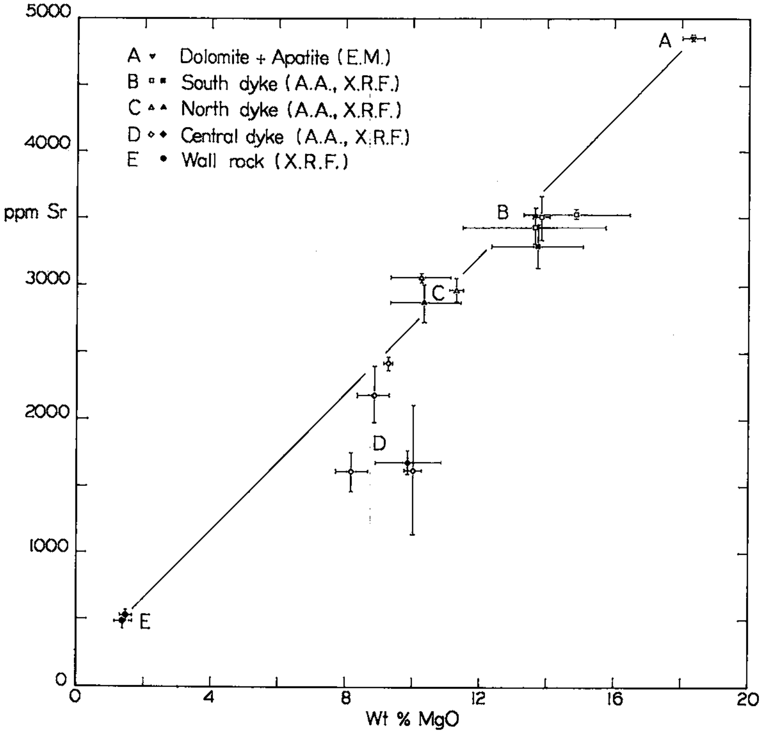

FIG. 11. Sr–MgO plot for specimens from the three dykes of the north quarry. Bars on lines represent precision in duplicate AA analyses and error in XRF analyses. A is the composition of average dyke-rock composed of dolomite and apatite, E is the composition of limestone.

dyke contains about 70% primary dyke material and 30% added limestone, the north dyke 55% primary material and 45% limestone, and the central dyke 40% primary material and 60% limestone. These calculations, of course, yield first approximations; departure from the straight line between limestone and dyke rock in Figure 11 can be ascribed to a number of factors, including the omission from our calculation of the contribution from xenoliths of basement metamorphic and igneous rocks, and addition and subtraction of Sr and Mg since dyke emplacement.

GENESIS

Development of carbonatites is normally explained by crystallization from a carbonate-rich magma. However, such features as quartz in direct contact with dolomite, scarcity of reaction rims in the wall rocks, low-Mg, low-Sr calcite adjacent to Sr-bearing dolomite, masses of kaolinite enclosed in dolomite, spherical carbonate grains, an incompatible assortment of megacrysts, splintered apatite crystals, and sub-vertical, deep striations in the wallrock at the dyke contact, cannot be explained by conventional mechanisms of carbonatite emplacement. Fluidization, however, would be consistent with many of the features observed. Our preferred model assumes a magnesium-rich carbonate magma at depth, fenitization of deep-seated wallrock, cooling of the magma *in situ*, buildup of CO_2 pressure, rupture of the overlying Precambrian and Paleozoic formations, and rapid introduction of material into the overlying fractures at least to the near-surface level of the Bobcageon Formation, largely as low-temperature, fluidized, solid particles.

The mechanism of fluidization is not a new concept in carbonatite modelling. It was proposed to explain 1) the formation of calcite-filled breccias at Lake Chilwa, Malawi (Smith 1956), 2) the occurrence of calcite microlites mixed with pyroclastic fragments in volcanos of the Elgon type in Uganda (Williams 1959), 3) random vertical banding, distension of xenolithic schlieren, random distribution of xenoliths and phenocrysts in rauhaugites of Rufunsa Gorge, Zambia (Bailey 1960, 1966a), and 4) the occurrence of calcite–magnetite spherules and size-sorted fragments at Tororo, Uganda (Sutherland 1980). The spheroidal or "pisolitic" nature of carbonates at Glenover and a number of other carbonatites in south and central Africa may also result from fluidization (Verwoerd 1966). Mineralogy and textures similar to those described here are present in carbonatite dykes and plugs near the Rufiji River, Tanzania, and in calcareous tuffs and agglomerates from the Basotu and Kerimasi craters, Tanzania (A.N. Mariano, pers. comm. 1987).

Some indication of pressures involved during emplacement of the Blackburn dykes can be obtained from the mineral associations microcline + dolomite, and dolomite + quartz. Thin reaction rims of calcite and phlogopite (Fig. 10) separate some microcline from dolomite but, in the same thin sections, no reaction is apparent between dolomite and quartz. In terms of the experimental equilibrium curves for dolomite + quartz + $H_2O \rightleftharpoons$ tremolite + calcite + CO_2, and dolomite + orthoclase + $H_2O \rightleftharpoons$ phlogopite + calcite + CO_2, at 2 kbar P_T, the mineral assemblages lie just within the stability fields of dolomite + quartz and calcite + phlogopite, as defined by Skippen (1974) and Puhan & Johannes (1974), but are not within the stability fields of these pairs at 1 kbar P_T (Skippen 1974, Bailey 1966b). At 2 kbar P_T the assemblages would be stable at $T < 490°C$ and $X(CO_2) < 0.8$. These data suggest that no equilibration took place below about 2 kbar P_T or at less than 6 km depth, thus implying rapid transfer from this depth to a location close to the surface.

We believe that dolomite and fluorapatite, with minor phlogopite and zircon, were primary precipitates from the early magma. Increased fluorine activity resulted in fluorine-enriched rims of phlogopite and fluorapatite. An influx of solutions, undersaturated in apatite, would cause some apatite to dissolve, thus accounting for resorption embayments on certain faces. The negative Ce anomaly in apatite is possibly connected with the occurrence of Ce^{4+}, implying extreme oxidation during the early stages of carbonatite development. Excess Ce resulting from rejection of Ce^{4+} in the apatite and carbonate structures may have led to a positive Ce anomaly in pyrochlore (Fig. 4). Fluorite may have been deposited at this stage. The F-depleted overgrowth on apatite crystals in the middle dyke may belong to a relatively late stage of growth and may represent deposition during a decline in F activity. Possibly the birefringence in this apatite is related to a high carbonate content as shown by McConnell (1973). This variety may have been formed during increased activity of CO_2.

An approximate temperature of equilibration of fluorine between apatite and phlogopite was obtained by the method of Chernysheva *et al.* (1976). This method gave 600 ± 20°C for a rim of apatite associated with a rim of Fe-poor phlogopite from both the north and south dykes. At this temperature, dolomite, quartz, calcite and phlogopite would have formed at a pressure considerably higher than 2 kbar, but it is also possible that this suite represents a later stage of equilibration than the one that involved apatite + phlogopite.

During intrusion, pieces of wallrock were detached and rafted upward. Xenoliths of Precambrian biotite–garnetiferous gneiss, granite pegmatite, fenitized wallrock, Paleozoic limestone and sandstone were thoroughly intermixed as they moved toward the surface. With the mélange of Precambrian xenocrysts derived from metamorphic and igneous rocks, xenocrysts from micaceous fenite and phenocrysts from the post-Paleozoic (Cretaceous) dykes, it is easy to understand the variation in phlogopite–biotite compositions over short distances, and it is equally easy to understand the discrepancy in Shafiqullah's phlogopite ages. Xenoliths scoured the limestone along the contact and friction produced some shearing in the wallrock. Temperatures were too low for appreciable metamorphism.

Granulation of dyke material was most intense near the contacts and resulted in local pseudo-chill zones. Particle streaming aligned mica and apatite megacrysts into a pseudo-trachytic texture. Gas bubbles were trapped, especially in layers of very fine-grained material. Their alignment and outlines (Fig. 9) are strikingly similar to those photographed by Lewis & Partridge (1967) during fluidization experiments.

During emplacement, attrition resulted in rounding of calcite and dolomite crystals, with secondary growth taking place in relatively quiescent periods between violent, explosive pulses. Some apatite crystals were rounded and some were broken and splintered. Zonal growth characterizes these crystals but overgrowth with unilateral development attests to final development prior to the last upward surge of particles. Some phlogopite megacrysts were bent and exfoliated during transport.

Late mineralization involved the introduction of low-temperature, low-Mg, low-Sr calcite, perhaps by circulating groundwater. This calcite replaced phlogopite, filled openings around quartz–feldspar xenoliths, corroded apatite, sealed fractures and filled vesicles. The composition of this calcite is almost identical with that of the wallrock, and may have been derived from it. A very late generation of pyrite and high-Mg calcite filled microfractures. These minerals were possibly also derived from the wallrock.

The origin of the kaolinite is uncertain. It may represent transported regolith from the Precambrian–Paleozoic interface. Such regolith has been observed at several places north of the Ottawa River (D.D.H., unpublished). The fact that some strongly kaolinized fragments are in direct contact with unaltered plagioclase precludes the possibility of kaolinization in the carbonatite after emplacement.

Dolomite in the hanging wall of the dyke in the south quarry does not seem to be related to the carbonatite. Its very low *REE*, Ba, Sr and Nb contents are in marked contrast with the footwall of this dyke and the other Blackburn dykes. The dolomite probably was deposited from epithermal solutions or groundwater, with the dolomite constituents derived either from the Ordovician sedimentary rocks or Precambrian marble.

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