

RARE EARTH ELEMENTS DISTRIBUTIONS AND
STRONTIUM ISOTOPE DATA FROM THE GEM PARK IGNEOUS COMPLEX, COLORADO

by

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INTRODUCTION

The origin of the alkaline rock complexes and their associated carbonatite bodies has been a source of continuing debate among petrologists. In the first part of this century, carbonatites were thought to have a non-magmatic origin. Shand (1930) and Daly (1933) proposed that feldspathoidal rocks and carbonatites were the result of desilication of a parent subalkaline magma, ranging in composition from basaltic to granitic, by reaction with partly dissociated carbonate. This hypothesis, known as the limestone assimilation hypothesis, was widely accepted by most petrologists.

However, there were some who still advocated a magmatic source for alkaline-carbonatite complexes. In 1960, through experimental petrology, Wyllie and Tuttle first demonstrated in the system $\text{CaO-CO}_2\text{-H}_2\text{O}$ that simple carbonatite magmas can exist at moderate temperatures through a wide pressure range. This evidence suggested a magmatic origin for carbonatites.

Further investigations by Watkinson and Wyllie (1964, 1969), Wyllie and Watkinson (1970), and Wyllie (1974) provided more experimental evidence contradicting the limestone assimilation hypothesis. Wyllie (1974) summarized the above arguments. He determined experimentally that a thermal barrier exists at low pressure between SiO_2 oversaturated liquids and liquids capable of precipitating feldspathoids. Consequently, Wyllie proved there is no way to generate alkaline magmas by desilication processes involving crystal-liquid reactions in granitic magmas in the crust.

Aside from the hypotheses of non-magmatic origin, two major groups of ideas explain the origin of carbonatites.

1. Carbonatite magmas are primary and juvenile (Dawson, 1964, 1966; von Eckermann, 1948; Holmes, 1952; Koster van Groos, 1975).

The primary carbonatite magmas react with silicate assemblages in the upper mantle or crust to form the alkaline rocks associated with carbonatites. This is known as the sial-syntexis hypothesis.

2. Carbonatite magmas have a derived origin. The carbonatite is formed as an immiscible liquid fraction from a parent melt such as carbonated alkali peridotite (Wyllie and Huang, 1976), carbonated nephelinite (Mitchell and Brunfelt, 1975), or ijolite (Koster van Groos and Wyllie, 1966, 1968, 1973) or as a residual liquid resulting from extensive fractional crystallization of an undersaturated ultrabasic magma (Wyllie and Haas, 1965, 1966; King and Sutherland, 1960; Watkinson, 1970; Watkinson and Wyllie, 1971).

Little work has been done using the distribution of the REE (rare earth elements) between carbonatites and cogenetic silicate rocks to clarify their origin and relationships. Only in the studies of Eby (1975) of the Oka carbonatite complex, Mitchell and Brunfelt (1975) of the Fen complex, and Cullers et al. (1976) of the Seabrook Lake and Callander Bay, Ontario, complexes were the REE used as genetic tracers.

This investigation determines the possible cogenetic relationships between the carbonatites and associated alkaline rocks of the Gem Park complex, Colorado. Thus, representative samples of carbonatite,

pyroxenite, gabbro, and nepheline syenite pegmatite from the Gem Park complex have been analyzed for major elements, for the REE, and initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios.

GEOLOGY

The Gem Park complex is about 11 miles northwest of Westcliffe, Colorado, and 21 miles southwest of Canon City, Colorado, on the border of Custer and Fremont counties (Fig. 1). It is a few miles southwest of the McClure Mountain mafic-ultramafic complex described by Christman et al. (1959). Heinrich and Anderson (1965) and Heinrich and Dahlem (1966) discussed the carbonatites and alkalic rocks of Fremont County, Colorado, including Gem Park briefly.

Parker et al. (1962) and Parker (1963) first presented more detailed descriptions of Gem Park. Parker and Sharp (1970) produced an extensive study of the complex upon which this investigation is based.

Gem Park, as described by Parker and Sharp (1970), is approximately two square miles in area. It is intruded into Precambrian gneiss and overlain by Tertiary volcanics. Gabbro and pyroxenite, the two main rock types, form units generally concentric with the circular outline of the complex (Fig. 2). This suggests that Gem Park may be a funnel-shaped layered body similar to the Iron Mtn.-McClure Mtn. complex (Shawe and Parker, 1968). Planar structures in the gabbro are concentric and dip consistently toward the center of the complex.

Both gabbro and pyroxenite are cut by dolomitic carbonatite dikes and irregular bodies of carbonatite. These dip more steeply toward the center of the complex than does the gabbro.

A large mass of fenite is in the central portion of the complex

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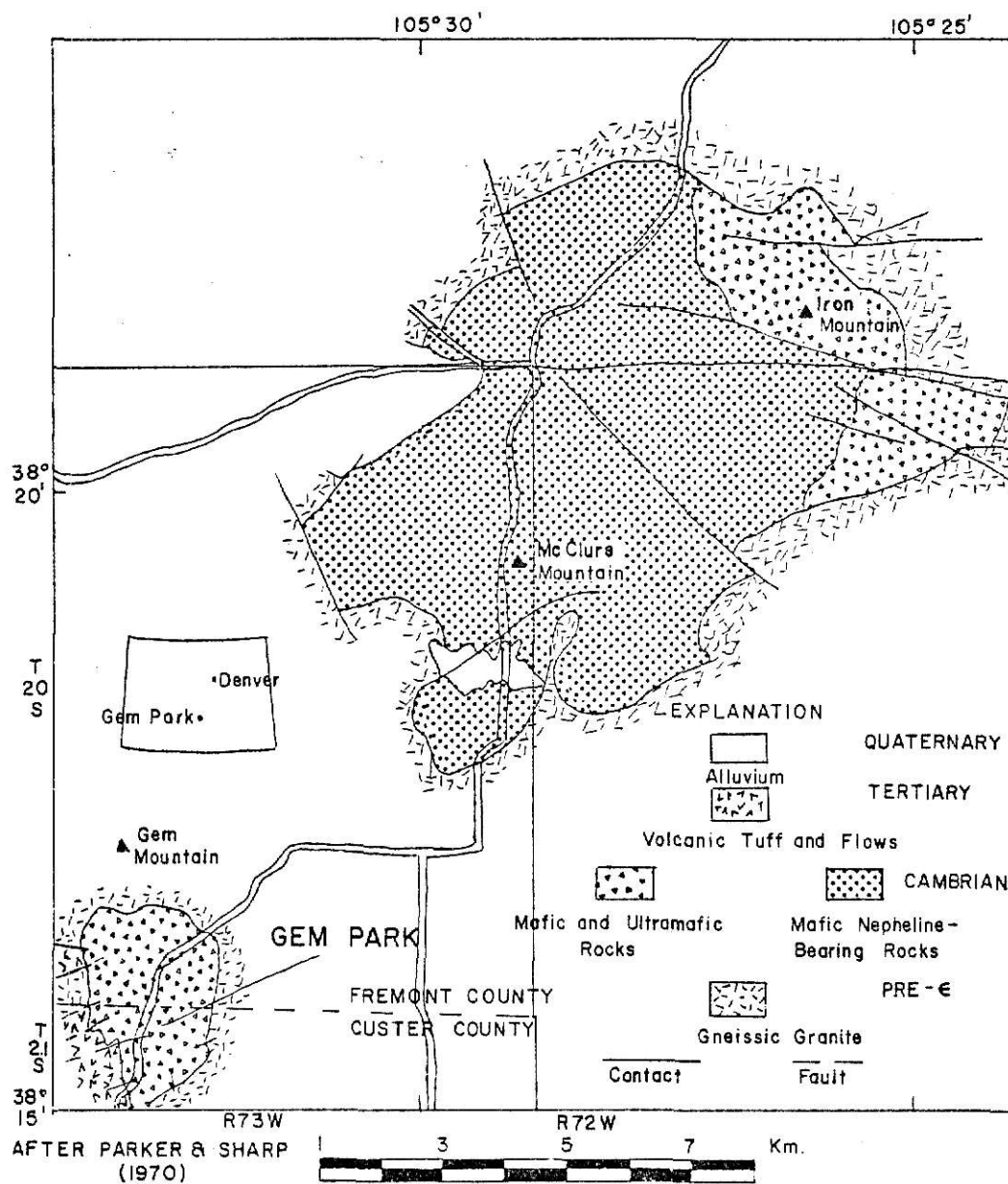


Figure 1. General geology and location map of the Gem Park and McClure Mountain ultramafic-mafic complexes.

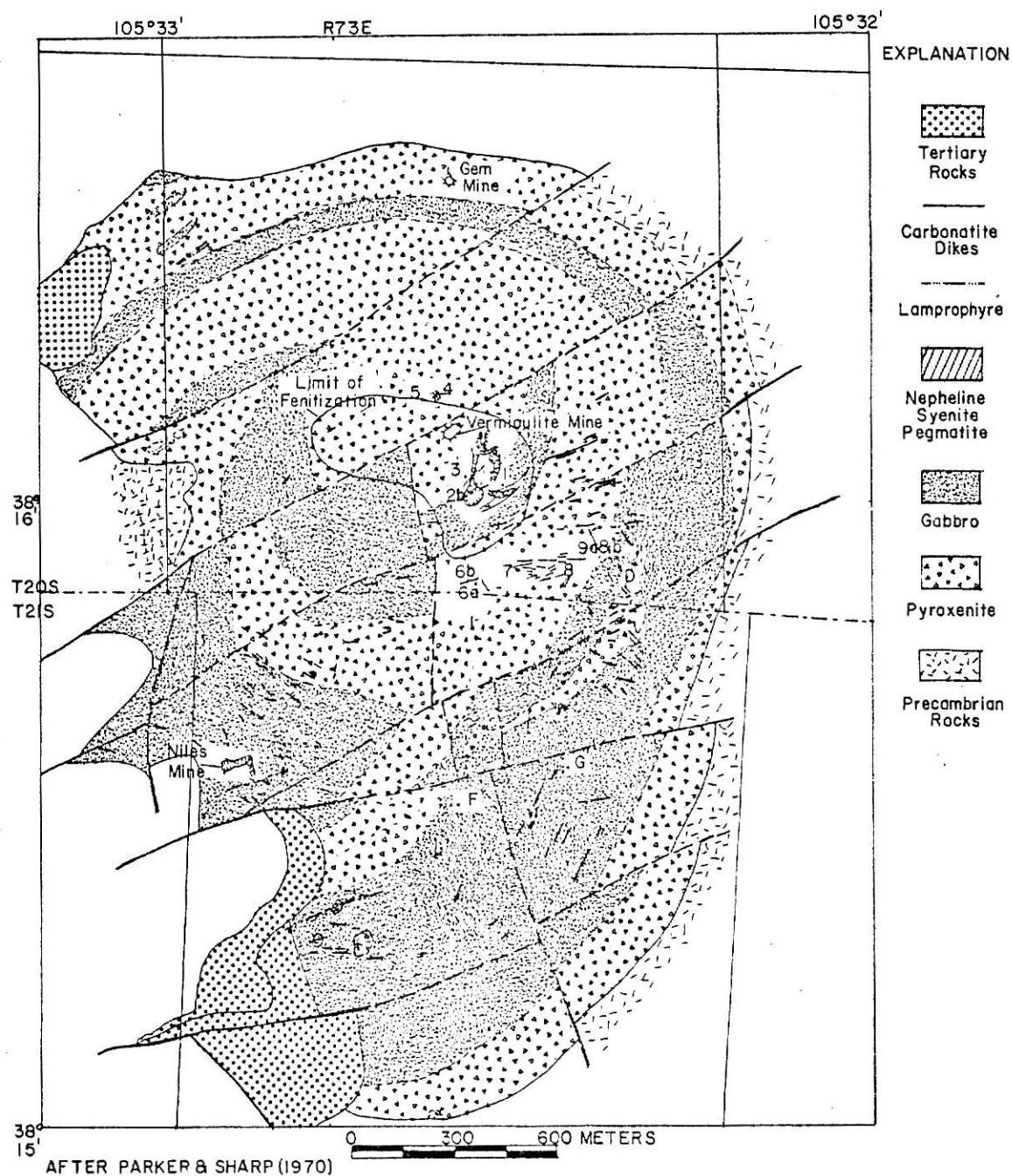


Figure 2. Geologic map of Gem Park showing the sample locations. All sample numbers correspond to location numbers except for GP-20, Location 4; GP-22 and GP-23, Location D; and GP-24, Location F.

(Fig. 2). Its position and the arrangement of the carbonatite dikes suggest that a large carbonatite body lies beneath the surface near the center of the complex (Parker and Sharp, 1970). This central location of the carbonatite mass is common in most carbonatite complexes (Tuttle and Gittins, 1966; Heinrich, 1966). Minor dikes and bodies of nepheline syenite pegmatite, lamprophyre and syenite porphyry occur within the complex.

R. F. Marvin of the U. S. Geological Survey has determined a K-Ar age of $551(\pm 55)$ m. y. B. P. on crocidolite from fenitized pyroxenite at the Vermiculite Mine in Gem Park (Parker and Sharp, 1970). This gives it a Cambrian age close to the range $508(\pm 15)$ to $532(\pm 27)$ m. y. B. P. determined by Marvin for McClure Mountain syenites (Parker and Sharp, 1970). The proximity and similar age for the two complexes suggest a genetic relationship between them.

EXPERIMENTAL METHODS

A Perkin-Elmer 305B atomic absorption spectrophotometer was used in most of the major element determinations. Buckley and Cranston (1970) described a procedure for multi-element atomic absorption analysis from a single decomposition of aluminosilicate. Their basic procedure including modifications made by Dr Sambhudas Chaudhuri was used to determine Al_2O_3 , MgO , total Fe, Na_2O , K_2O , and TiO_2 .

G. K. Hoops of the University of Texas analyzed the samples for SiO_2 and total Fe according to the procedure of Shapiro and Brannock (1962). He also helped in CaO and MgO determinations using the methods described by Abbey (1968).

MnO and Na_2O were determined by INAA (instrumental neutron activation analysis) by Rich Koch of Kansas State University. The INAA Na_2O values served as a check on the atomic absorption determinations. CO_2 was determined by loss on ignition.

Standard solutions were prepared from Fisher Scientific stock solutions. Exact concentrations and procedures are given in Appendix A. Standard rocks, BCR-1 and AGV-1, were analyzed with each group of samples as an external standard. The results of these analyses are given in Appendix A.

The REE were analyzed by radiochemical neutron activation using a group separation of the REE and a high resolution GeLi detector (Denechaud et al., 1970; Cullers et al., 1974).

The results for BCR-1 obtained by Cullers et al. (1974) agree well with other analysts. Appendix B contains a description of the analytical

procedure.

Chaudhuri (1966) and Chaudhuri and Brookins (1969) described the method used in determining the $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratios for the Gem Park samples. A hydrofluoric-perchloric acid mixture was used to dissolve samples of less than 100 mesh. They were brought into final solution using hydrochloric acid. Rb and Sr were concentrated by ion exchange. A six-inch radius, single filament, solid source mass spectrometer was used for the isotopic measurements.

The Rb and Sr contents were determined by isotope dilution. These had been previously estimated by the x-ray fluorescence procedure described by Lee (1972). The $\text{Sr}^{87}/\text{Sr}^{86}$ ratios were corrected for fractionation by normalizing the $\text{Sr}^{86}/\text{Sr}^{88}$ ratios to 0.1194. Appendix C gives a description of the sample dissolutions used in the Rb-Sr analyses.

PETROGRAPHY

General Descriptions

The following are brief petrographic descriptions of the major rock types in the Gem Park complex. Figure 2 is a general map of the area that includes the locations from which samples for this study were collected. Appendix D contains point counted modal analyses of 1300 points, more detailed descriptions for the samples analyzed and other representative samples from the complex.

Pyroxenites

Parker and Sharp (1970) described two principal varieties of pyroxenite at Gem Park -- coarse and medium-grained. The coarse-grained pyroxenite crops out along the periphery of the complex in the north, east, and south sides and forms discontinuous masses within the complex. On the west, the boundary of the complex is concealed by Tertiary volcanic rocks.

Both varieties of pyroxenite occur also in the central part of the complex in the area surrounding the Vermiculite Mine and in the low hills to the south and east of the mine. The pyroxenite units form a concentric ring-shaped map pattern, centered at the Vermiculite Mine.

Sample GP-3 is typical of the coarse-grained pyroxenites studied. It is a holocrystalline, xenomorphic-granular, pyroxenite composed of 73 per cent randomly-oriented, subhedral to anhedral augite grains

with interstitial plagioclase. Approximately 2 per cent kaersutite occurs as unreacted single grains which may be trapped intercumulus primary melt.

GP-6 is a typical medium-grained pyroxenite that contains considerably more plagioclase (23 per cent) than the medium-grained pyroxenites analyzed by Parker and Sharp (1970). It is a holocrystalline, xenomorphic-granular pyroxenite containing clumps of randomly-oriented, subhedral to anhedral augite grains showing reaction rims of brown and green amphibole (kaersutite). About 2 per cent of the kaersutite may be primary. It has some interstitial plagioclase as well as 23 per cent randomly-oriented, heavily-sericitized, anhedral laths of labradorite (An₅₉) segregated into clumps by augite and amphibole grains.

Both GP-3 and GP-6 show cumulate textures and will be treated as such in this investigation.

Gabbro

Gabbro and pyroxenite are mutually associated throughout the complex and either may be enclosed in the other as layers, lenses, or discordant bodies (Parker and Sharp, 1970). Gabbro crops out predominantly in the southern part of the complex and at its center, west of the Vermiculite Mine (Fig. 2).

Parker and Sharp (1970) described several varieties of gabbro differing in their proportions of pyroxene, plagioclase, and olivine and in their grain size.

GP-1g is a typical Gem Park gabbro containing 44 per cent

subhedral to anhedral augite grains and 40 per cent anhedral labradorite (An_{62}) laths and minor amounts of pleochroic brown and green amphibole (kaersutite). Texturally, it is a medium-grained, holocrystalline, xenomorphic-granular, gabbro.

Nepheline Syenite Pegmatite and Other Minor Intrusives

The nepheline syenite pegmatite at Gem Park is exposed in one outcrop, a few feet in diameter, in a shallow pit about 1000 feet northwest of the Vermiculite Mine. Syenite fragments can be found in the soil for a few hundred feet to the north and west of the pit. The pegmatite seems to intrude pyroxenite (Parker and Sharp, 1970).

Sample GP-4 is a holocrystalline, hypidiomorphic-granular, coarse-grained, nepheline syenite pegmatite containing 35 per cent anhedral nepheline grains, 60 per cent anhedral perthite grains and minor amounts of aegirine, sphene, and iron ore.

Small lamprophyre and syenite porphyry dikes also intrude the Gem Park rocks. The lamprophyre dikes, tentatively classed as spessartite by Parker and Sharp (1970), are 500 feet southwest of the Niles Mine at the southwest edge of the complex and in the Vermiculite Mine in the center of the complex. A petrographic description of a lamprophyre sample is in Appendix A.

Syenite porphyry dikes are in the extreme northwest corner of Gem Park. They cross-cut gabbro and pyroxenite and extend into the bordering gneissic granite. Parker and Sharp (1970) described them as being similar to the other dikes that occur throughout the Wet

Mountains region. These dikes and the lamprophyres were not included in the other analyses because the purpose of this study was to examine the possible genetic relationships among the rock types. Unfortunately, there was not sufficient time to include these small intrusions.

Carbonatite Dikes

Gem Park carbonatite dikes are rauhaugites (Heinrich, 1966). Parker and Sharp (1970) divided them into groups based on their trends and mineralogy. In the southeast part of the complex, a group of dikes trend roughly parallel to the contact of the complex and are tangential to its concentric structure. They appear to be arranged concentrically about a zone in the central part of the complex.

The group of dikes along the east side of the complex are approximately perpendicular to the tangential dike set and are arranged radially about the zone in the central part of the complex. Other groups of radial and tangential dikes along the west side of the complex appear to originate from the north-central part of the complex near the Vermiculite Mine. A centrally-located unexposed carbonatite mass is suggested by the concentric and radial carbonatite dikes (Parker and Sharp, 1970).

On the basis of mineralogy, Parker and Sharp (1970) distinguished four varieties of carbonatite dikes: dolomite-apatite, dolomite-blue amphibole-pyroxhlore, dolomite-pyroxhlore, and dolomite-barite-monazite. Samples of carbonatite examined in this study included GP-6b and GP-8, dolomite-apatite dikes; GP-7b, a dolomite-pyroxhlore dike; GP-9a&b, a dolomite-blue amphibole-pyroxhlore dike.

Fenite

The term fenite describes a rock which has been altered by alkali metasomatism at the contact of a carbonatite intrusive complex (Glossary of Geology, 1973). At Gem Park, fenite occurs in gabbro and pyroxenite over a large area near the old Vermiculite Mine and at the borders of some carbonatite dikes (Fig. 3a and b). Fenite occurs in the surrounding gneissic granite enclosing carbonatite dikes and bodies, in quartzite inclusions contained in gabbro and pyroxenite, and in gneissic granite at the border of the complex.

Figure 2 shows the most extensive fenite in Gem Park. It occurs in pyroxenite and gabbro which underlie an oval-shaped area about 450 m long in the north-central part of the complex.

In the old Vermiculite Mine and other pits and prospects in Figure 2, the altered rocks are exposed. Parker and Sharp (1970) described pyroxenite and gabbro as having been fenitized to a variable assemblage of fibrous blue sodic amphibole, aegirine, tremolite-actinolite, augite, phlogopite, vermiculite, dolomite, calcite, barite, apatite, and magnetite. Fenite was not included in this investigation.



Fig. 3a



Fig. 3b

Figure 3. Carbonatite dike showing inclusions of gabbro and pyroxenite, Location G.

Fig. 3a: Inclusion of gabbro showing fenitized rim and unaltered core.

Fig. 3b: Inclusion of pyroxenite showing fenitized rim and unaltered core.

RESULTS

Major Elements

Major elements were analyzed in representative samples of the major rock types in the Gem Park complex and the CIPW norms were calculated (Table 1). They include the following: four samples of carbonatite, GP-6b, GP-7b, GP-8, GP-9a&b; one gabbro, GP-1g; two pyroxenites, GP-3 and GP-6; and one nepheline syenite pegmatite, GP-4.

The gabbro, GP-1g, and pyroxenites, GP-3 and GP-6, are metaluminous (Hyndman, 1972). The nepheline syenite pegmatite, GP-4, is miaskitic, i.e., $\frac{\text{Na}_2\text{O}+\text{K}_2\text{O}}{\text{Al}_2\text{O}_3}$ is less than 1., (Sorensen, 1974), a variety often associated with carbonatites.

The analyses determined in this study correspond closely with those of Parker and Sharp (1970) on samples of Gem Park gabbro and pyroxenite (Tables 1 and 2). Pyroxenite, GP-3, is similar in major elements to pyroxenite, WM-64-875, analyzed by Parker and Sharp as is gabbro, GP-1g, to their gabbro, WM-64-859.

Table 2 gives the chemical composition of a representative pyroxenite (N35C) and nepheline syenite (N121) from Napak (King and Sutherland, 1966). It also lists a range of compositions for pyroxenites and nepheline syenites from other alkaline complexes as compiled by Hyndman (1972). These compare relatively closely with Gem Park analyses.

Gem Park carbonatites compare closely with the average carbonatite composition given by Gold (1963; Table 2). They are significantly lower in SiO_2 and Al_2O_3 than Gold's average carbonatite except that GP-7b

Table 1. Major Element Contents and Mineral Norms for Gem Park
Whole Rocks in Per Cent by Weight

	Gabbro GP-1g	Carbonatite GP-8	Neph. Syen. Peg. GP-4	Pyroxenite GP-3
SiO ₂ *	39.84	0.06	59.47	44.50
TiO ₂	2.14	2.92	3.25	2.97
Al ₂ O ₃	11.33	---	20.53	6.01
Fe ₂ O ₃ **	19.68	4.18*(2.96)	2.86	8.87*(9.17)
MnO*	0.18	0.64	0.05	0.14
MgO	9.62	18.21*	0.15	12.23*
CaO*	13.71	31.98	0.97	20.52
Na ₂ O	1.47	0.30	8.11	1.83
K ₂ O	0.14	0.14	8.97	0.18
CO ₂	---	45.17	---	---
Total	98.11	103.59	104.36	97.25
q	---	---	---	---
or	---	---	52.99	---
ab	---	---	19.93	---
an	20.03	---	---	7.79
ne	6.82	---	19.32	8.24
ac	---	---	---	---
ns	---	---	3.00	---
di-di	10.83	---	0.87	45.26
di-hd	11.60	---	---	13.15
wo	---	---	1.05	---
hy-en	---	---	---	---
hy-fs	---	---	---	---
ol-fo	13.37	---	---	6.61
ol-fa	17.93	---	---	2.24
il	4.09	---	5.54	5.61
lc	6.55	---	---	0.87
cs	6.56	---	---	6.56
pf	---	---	0.56	---

* SiO₂, CaO, Fe₂O₃, and MgO - G. K. Hoops, analyst; MnO - Rich Koch, analyst

** Total Fe as Fe₂O₃

() My AA values for Fe₂O₃

Table 1. Major Element Contents and Mineral Norms for Gem Park
Whole Rocks in Per Cent by Weight (continued)

	Carbonatite GP-9a&b	Pyroxenite GP-6	Carbonatite GP-7b	Carbonatite GP-6b
SiO ₂ *	0.68	37.31	32.24	0.82
TiO ₂	4.74	5.24	2.72	4.60
Al ₂ O ₃	---	11.73	---	---
Fe ₂ O ₃ **	4.15	22.34	1.76	12.01
MnO*	0.53	0.17	0.27	0.40
MgO	17.30	11.17	11.68	14.56
CaO*	31.98	13.61	21.18	29.05
Na ₂ O	0.19	1.10	0.06	0.32
K ₂ O	0.08	0.84	0.12	0.12
CO ₂	41.76	---	28.09	34.95
Total	101.41	103.51	98.12	96.83
q	---	---	---	---
or	---	---	---	---
ab	---	---	---	---
an	---	24.48	---	---
ne	---	5.11	---	---
ac	---	---	---	---
ns	---	---	---	---
di-di	---	6.49	---	---
di-hd	---	5.42	---	---
wo	---	---	---	---
hy-en	---	---	---	---
hy-fs	---	---	---	---
ol-fo	---	17.59	---	---
ol-fa	---	19.77	---	---
il	---	10.02	---	---
lc	---	3.93	---	---
cs	---	9.13	---	---
pf	---	---	---	---

* SiO₂, CaO, Fe₂O₃ and MgO - G. K. Hoops, analyst; MnO - Rich Koch, analyst

** Total Fe as Fe₂O₃

() My AA values for Fe₂O₃

Table 2. Major Element Analyses from Other Alkaline Complexes in Per Cent by Weight

	Gem Park ¹		Napak ²		Range of ³		Range of ³		Average ⁴
	Gabbro WM-64-859	Pyroxenite WM-64-875	Pyroxenite N35C	Nepheline Syenite N121	Nepheline Syenites	Pyroxenites	Pyroxenites	Carbonatite IV	
SiO ₂	39.16	45.31	41.39	51.32	43.18-51.03	31.28-51.12	11.99		
Al ₂ O ₃	13.72	7.03	4.91	21.92	8.48-18.22	1.52-15.84	3.52		
Fe ₂ O ₃	7.50	3.98	10.37	5.92	3.65-7.61	0.39-16.33	3.09		
FeO	9.79	6.05	9.77	2.71	2.67-5.28	2.65-12.63	3.74		
MgO	6.68	12.84	10.06	0.94	3.41-13.01	3.97-23.15	5.59		
CaO	12.12	19.99	18.02	3.95	6.96-10.63	10.26-30.72	34.80		
Na ₂ O	2.56	0.82	1.52	7.60	3.44-6.43	0.25-6.77	0.42		
K ₂ O	0.45	0.17	1.40	5.10	0.56-4.83	0-4.74	1.48		
H ₂ O ⁺	1.06	0.63	---	0.11	---	---	---		
H ₂ O ⁻	0.10	0.21	---	---	---	---	---		
TiO ₂	4.42	2.50	2.55	0.07	0.71-1.40	0.32-9.02	0.79		
P ₂ O ₅	1.06	0.14	0.02	0.76	0.60-2.20	0-4.33	0.76		
MnO	0.21	0.15	0.21	0.19	0.03-0.28	0.05-0.36	0.60		
CO ₂	0.99	0.40	---	0.16	0-5.42	0-2.08	28.47		
Cl	0.04	0.02	---	---	---	---	---		
F	0.12	0.04	---	---	---	0-0.12	0.87		
Subtotal	99.98	100.28	100.22	100.75				98.75	
Less O	0.06	0.02							
TOTAL	99.92	100.26							

- (1) Parker and Sharp (1970)
 (2) King and Sutherland (1966)
 (3) Hyndman (1972)
 (4) Gold (1963)

contains 33 per cent secondary vein quartz. Their MgO content is higher because they are dolomitic. They also contain a significantly greater percentage of TiO_2 than the average carbonatite described by Gold (1963).

Sr Isotopic Data

Initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios were determined for gabbro (GP-1g), pyroxenite (GP-3), nepheline syenite pegmatite (GP-20), and carbonatites (GP-6b, GP-8, GP-9a&b, GP-22, GP-23). The results are comparable to those determined for similar rock types from other alkaline complexes (Tables 3 and 4).

All the Gem Park samples, alkaline rocks and carbonatites, have low similar $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratios ($0.7028-0.7038 \pm 0.001$) with the exception of GP-9a&b which has a high initial Sr ratio of 0.7056 (Table 3). This is still within the range of carbonatite values cited by Faure and Powell (1972), 0.7016-0.7075, but it is significantly higher than the initial Sr ratios of gabbro, GP-1g, and pyroxenite, GP-3.

The nepheline syenite pegmatite has a higher initial Sr ratio than the other alkaline rocks, 0.7038. It is similar to that determined for a nepheline syenite from Magnet Cove, Arkansas (Table 4).

Table 3. Isotopic Data for Gem Park Whole Rock Samples

Sample No.	Rb, ppm	Sr, ppm	($\text{Sr}^{87}/\text{Sr}^{86}$) Isotope Ratio	($\text{Sr}^{87}/\text{Sr}^{86}$) Isotope Dilution
GP-1g, Gabbro	-	356	-	0.7027 $\pm$ 0.001*
GP-3, Pyroxenite	-	256	0.7028 $\pm$ 0.001*	-
GP-20, Nepheline Syenite Pegmatite	4.9	583	0.7040 $\pm$ 0.001 (0.7038) _o	-
GP-6b, Carbonatite	-	-	0.7036 $\pm$ 0.001*	-
GP-8, Carbonatite	-	-	0.7037 $\pm$ 0.001*	-
GP-9a&b, Carbonatite	-	-	0.7056 $\pm$ 0.001*	-
GP-22, Carbonatite	-	-	0.7038 $\pm$ 0.001*	-
GP-23, Carbonatite	-	-	0.7036 $\pm$ 0.001*	-

* These are initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio estimates.

Table 4. Sr Isotopic Data From Other Alkaline Complexes

Sample	Rock Type and Locality	Reference	$(\text{Sr}^{87}/\text{Sr}^{86})_0$
GP-6b	Carbonatite, Gem Park	This work	0.7036 ± 0.001
GP-8	Carbonatite, Gem Park	This work	0.7037 ± 0.001
GP-9a&b	Carbonatite, Gem Park	This work	0.7056 ± 0.001
GP-22	Carbonatite, Gem Park	This work	0.7038 ± 0.001
GP-23	Carbonatite, Gem Park	This work	0.7037 ± 0.001
	Dolomitic Carbonatite, eastern Uganada	Bell et al. (1970)	0.7035 ± 0.001
	Carbonatite, Rocky Boy, Montana	Powell et al. (1966)	0.7057 ± 0.0012
	Carbonatite, Oka, Quebec	Powell et al. (1966)	0.7032 ± 0.0012
	Carbonatite, McClure Mtn., Colorado	Fenton and Faure (1970)	0.7053 ± 0.0005
GP-20	Nepheline Syenite Pegmatite, Gem Park	This work	0.7038 ± 0.001
	Nepheline Syenite, Magnet Cove, Arkansas	Powell et al. (1966)	0.7035 ± 0.0006
GP-1g	Gabbro, Gem Park	This work	0.7027 ± 0.001
	Stillwater Complex, Montana	Fenton and Faure (1969)	0.7029 ± 0.0006
GP-3	Pyroxenite, Gem Park	This work	0.7028 ± 0.001
	Pyroxenite, Iron Hill, Colorado	Powell et al. (1966)	0.7013 ± 0.0014

Rare Earth Elements

Gabbro.--Gem Park gabbro, GP-24, shows a REE distribution in the range for alkali-rich basalts (Fig. 4, Kay and Gast, 1973). It has a moderate total REE abundance ($\Sigma\text{REE} = 116$ ppm), and it has a La/Lu ratio of 5.8 (Table 5, Fig. 4).

The other gabbro analyzed, GP-1g, had an unusual REE distribution (Fig. 4). It is depleted in the light REE but similar to gabbro, GP-24, in the middle to heavy REE. GP-1g has a moderate REE abundance ($\Sigma\text{REE} = 86$ ppm) and a La/Lu ratio of 2.7 (Table 5).

Pyroxenite.--The two Gem Park pyroxenites that were analyzed for the REE have distinctly different REE abundances (Table 5, Fig. 5), but they have similar La/Lu ratios to one another (Table 5). Pyroxenite, GP-6, has a low total REE abundance ($\Sigma\text{REE} = 57$ ppm), and a REE distribution similar to alkali-rich basalts (Fig. 5; Kay and Gast, 1973). It contains about 10 per cent cumulate plagioclase and about 13 per cent interstitial plagioclase.

Pyroxenite, GP-3, contains only about one per cent interstitial plagioclase. It has a higher total REE abundance than GP-6 ($\Sigma\text{REE} = 291$ ppm) (Table 5; Fig. 5). On the chondrite-normalized curve, Ce is slightly enriched over La.

Nepheline Syenite Pegmatite.--Nepheline syenite pegmatite, GP-4, is strongly enriched in the light REE, but depleted in the middle and heavy REE (Fig. 6). This nepheline syenite has a similar REE distribution to nepheline syenite from Magnet Cove, Arkansas (R. L. Cullers,

Table 5. REE Concentrations (ppm) in Gem Park Whole Rock Samples

Sample	La	Ce	Sm	Eu	Gd	Tb	Ho	Yb	Lu	Σ REE*	La/Lu, chondrite normalized
Gabbro, GP-1g	6.43	22.62	6.02	1.99	7.39	1.05	0.88	1.59	0.52	86.3	2.7
Gabbro, GP-24	16.50	37.0	6.61	1.88	7.0	0.87	0.81	1.60	0.29	116.2	5.9
Pyroxenite, GP-6	6.73	18.17	3.32	1.08	---	0.43	---	0.74	0.09	57.5	7.0
Pyroxenite, GP-3	29.65	91.31	18.44	5.86	16.73	2.44	0.42	3.18	---	291.4	6.5
Nepheline Syenite Pegmatite, GP-4	42.93	52.16	1.53	0.59	---	0.44	0.33	1.69	---	129.2	14.0
Carbonatite, GP-8	58.09	217.28	8.53	2.30	3.35	0.53	---	1.68	0.19	403.5	31.5
Carbonatite, GP-6b	204.95	593.33	67.28	17.99	56.49	5.79	---	3.91	---	1469.8	30.4
Carbonatite, GP-9a&b	113.71	351.97	21.14	5.87	4.40	1.30	---	1.18	0.12	728.7	98.4
Carbonatite, GP-7b	226.11	517.71	24.35	7.36	6.21	1.75	---	1.47	0.23	1073.8	102.29

* REE contents not analyzed in this study are estimated by interpolation from chondrite-normalized curves.
Y is not included in the REE.

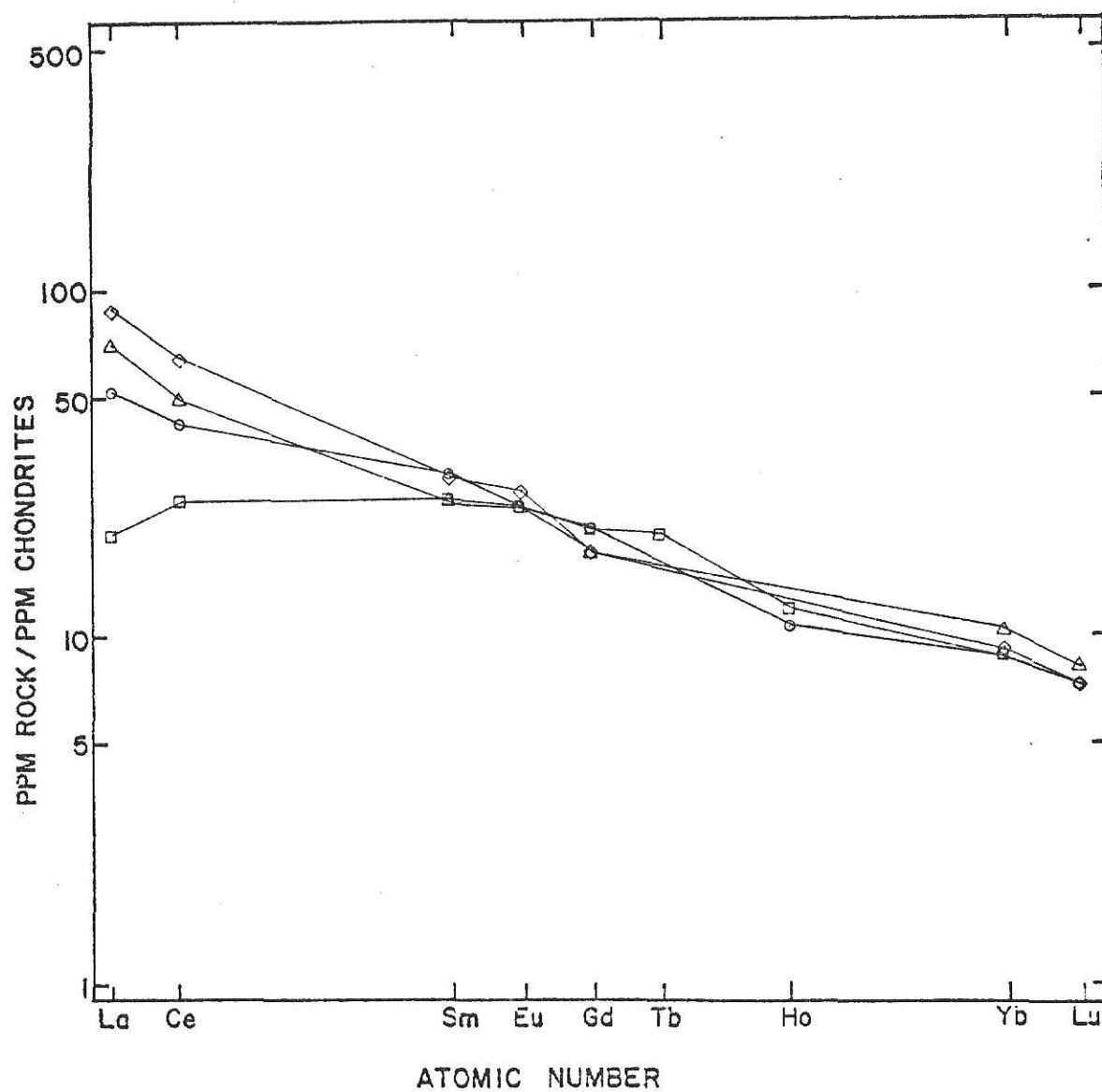


Figure 4. RFE distributions for Gem Park gabbros, GP-24 (O) and GP-1g (□), compared to alkali basalts, 04 (Δ) and K12 (◇), (Kay and Gast, 1973).

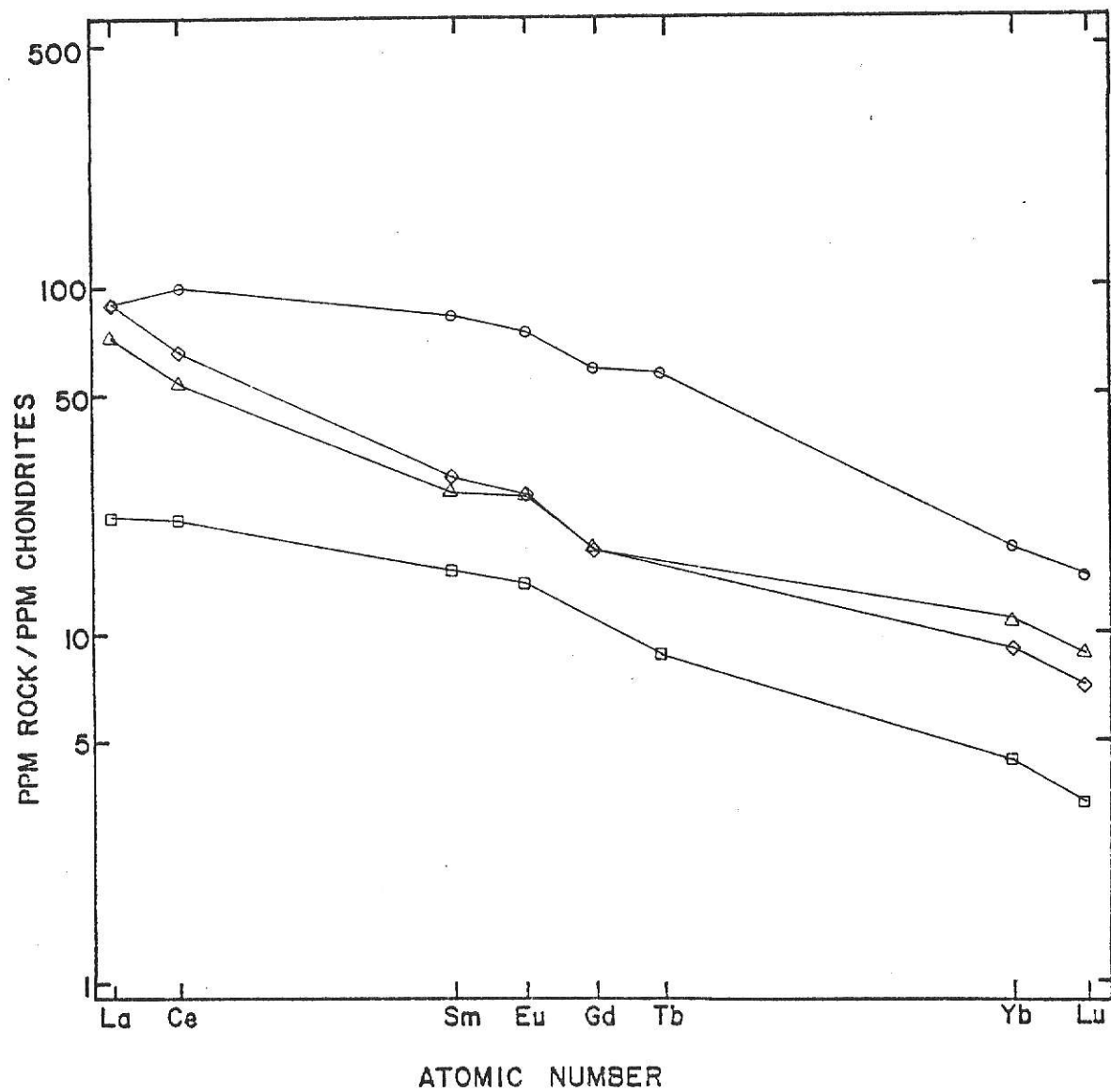


Figure 5. RREE distributions for the Gem Park pyroxenites, GP-6 (□) and GP-3 (O), compared to alkali basalts, 04 (Δ) and K12 (◇), (Kay and Gast, 1973).

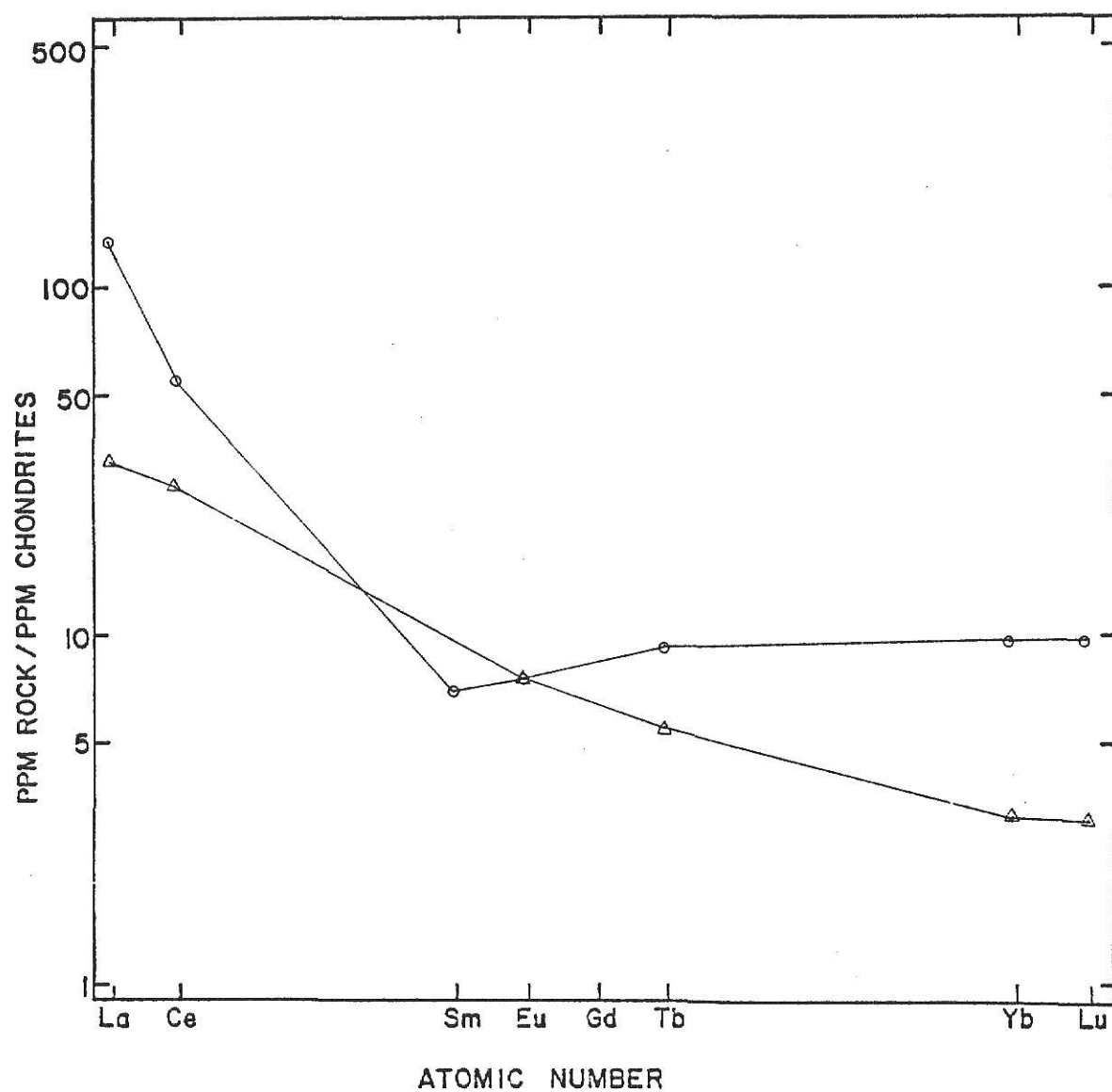


Figure 6. REE distributions for Gem Park nepheline syenite pegmatite, GP-4 (O), compared to a nepheline syenite (Δ) from the Fen complex, Norway (Mitchell and Brunfelt, 1975).

personal communication), and from the Fen Complex, Norway (Mitchell and Brunfelt, 1975; Fig. 6). GP-4 has a moderate REE concentration ($\Sigma\text{REE} = 129$ ppm), and a La/Lu ratio of 14.4 (Table 5).

Carbonatite.--Gem Park carbonatites have typical carbonatite REE distributions with high absolute REE contents and high light to heavy REE ratios (Fig. 7; Table 5) similar to results obtained by Eby (1975), Loubet et al. (1972), Mitchell and Brunfelt (1975) and Cullers et al. (1976) (Table 6). The REE distributions in Figure 7 were determined by dividing the concentration of each REE in each sample by a composite chondritic concentration of the REE (Haskin et al., 1968). Ratios of La/Lu were calculated from this chondrite-normalized value rather than their actual concentration in the samples.

Both Cullers et al. (1976) and Eby (1975) determined REE for carbonatites that are considerably higher than those obtained for Gem Park (Table 6). Eby (1975) also obtained higher La/Lu ratios for Oka sovites than those determined for Gem Park rauhaugites (Table 6). Cullers et al. (1976) determined a La/Lu ratio for a Seabrook Lake sovite that is comparable to those of the Gem Park samples (Table 6).

Mitchell and Brunfelt (1975) listed La/Yb ratios for Fen rauhaugites which are comparable to those of the Gem Park samples (Table 6). In fact, their sample 108 has a La/Yb ratio of 87.13, which is identical to the La/Yb ratio for GP-7b. They also found a slight Ce anomaly on the chondrite-normalized curve, i.e., Ce is higher than La, for their coarse-grained sovites. Gem Park rauhaugites, GP-9a&b, GP-6b, and GP-8, show a similar anomaly (Fig. 7).

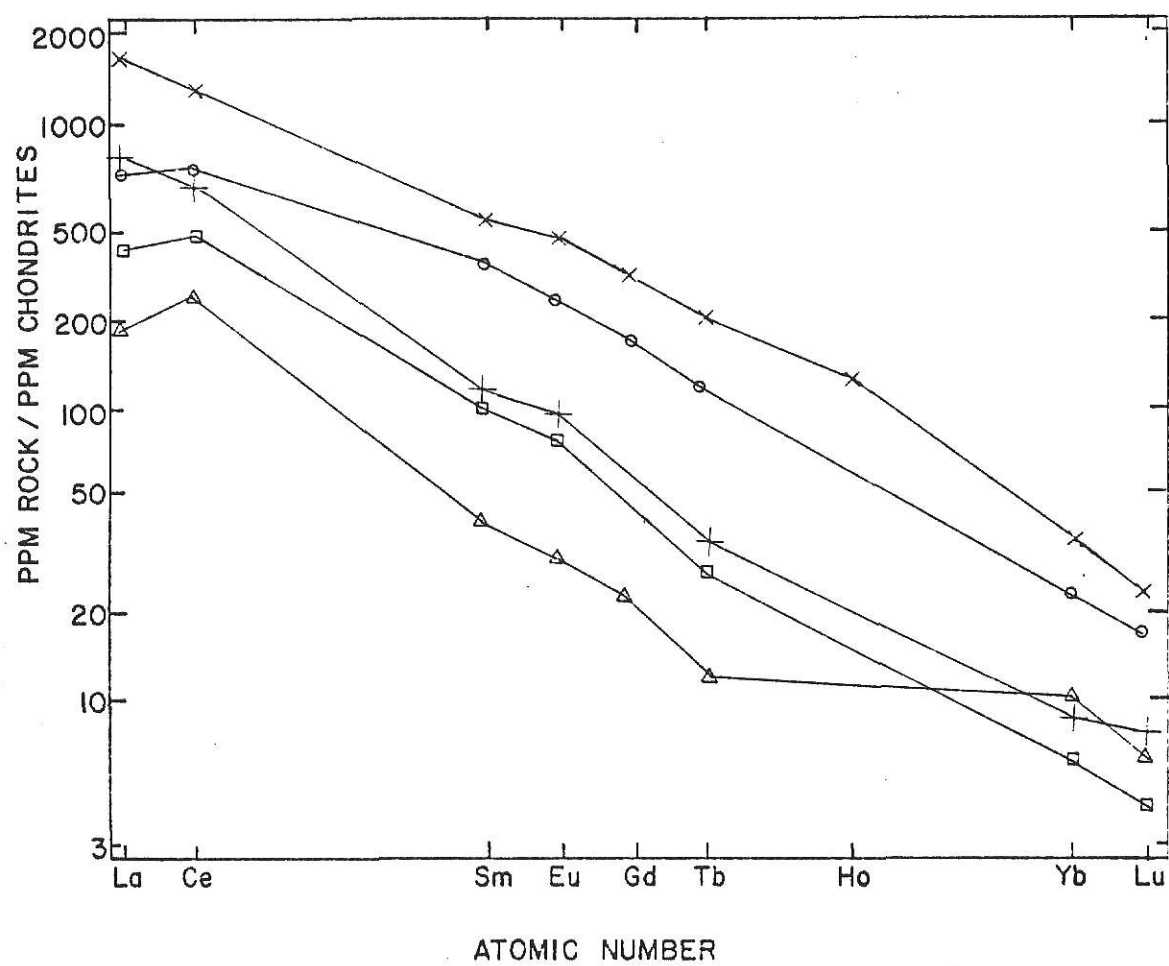


Figure 7. REE distributions for the Gem Park carbonatites, GP-8 (Δ), GP-9a&b ($\square$), GP-6b ($\circ$), and GP-7b ($+$), compared to a sovite ($\times$) from Seabrook Lake, Ontario (Cullers et al., 1976).

Table 6. A Comparison of REE Contents for Gem Park and Other Carbonatites

	Σ REE (ppm)	La/Lu, chondrite normalized
Ranges for Gem Park carbonatites	403.5-1469.8	30.4-102.29
Seabrook Lake sovites (Cullers et al., 1976)	2493	74.4
Oka sovites (Eby, 1975)	5100-8500	216.6-380
Fen rauhaugites (Mitchell and Brunfelt, 1975)	-----	31.9-87.1*

* La/V_P ratios

DISCUSSION

Major Element Data

Major element analyses for the Gem Park samples suggest possible genetic relationships among the rock types. Samples GP-1g, gabbro, GP-3 and GP-6, pyroxenites, and GP-4, nepheline syenite pegmatite were plotted on an AFM diagram according to their $\text{Na}_2\text{O}+\text{K}_2\text{O}$ (A), MgO (M), and FeO (F) molecular percent (Fig. 8).

The pyroxenites and nepheline syenite pegmatite fall on a curve along the low MgO portion of the diagram. Alkali content increases along this trend from GP-6, the plagioclase-rich pyroxenite, to GP-3, pyroxenite, to GP-4, nepheline syenite pegmatite. In contrast, gabbro, GP-1g, is at a point of high FeO, moderate MgO, and low alkali content.

Based on this major element data, it appears that Gem Park gabbros and pyroxenites may not be the result of a single differentiation sequence. The position of the curve connecting the compositions of the pyroxenites and nepheline syenite pegmatite suggests the possibility of a genetic relationship among these rock types. However, the gabbro, GP-1g, appears to have a different source.

Sr Isotopes

Initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios determined for samples of Gem Park gabbro and pyroxenite suggest the possibility of a comagmatic origin for these rock types (Table 3). Because the initial Sr ratios are low, 0.7027 and 0.7028, respectively, an upper mantle source is indicated.

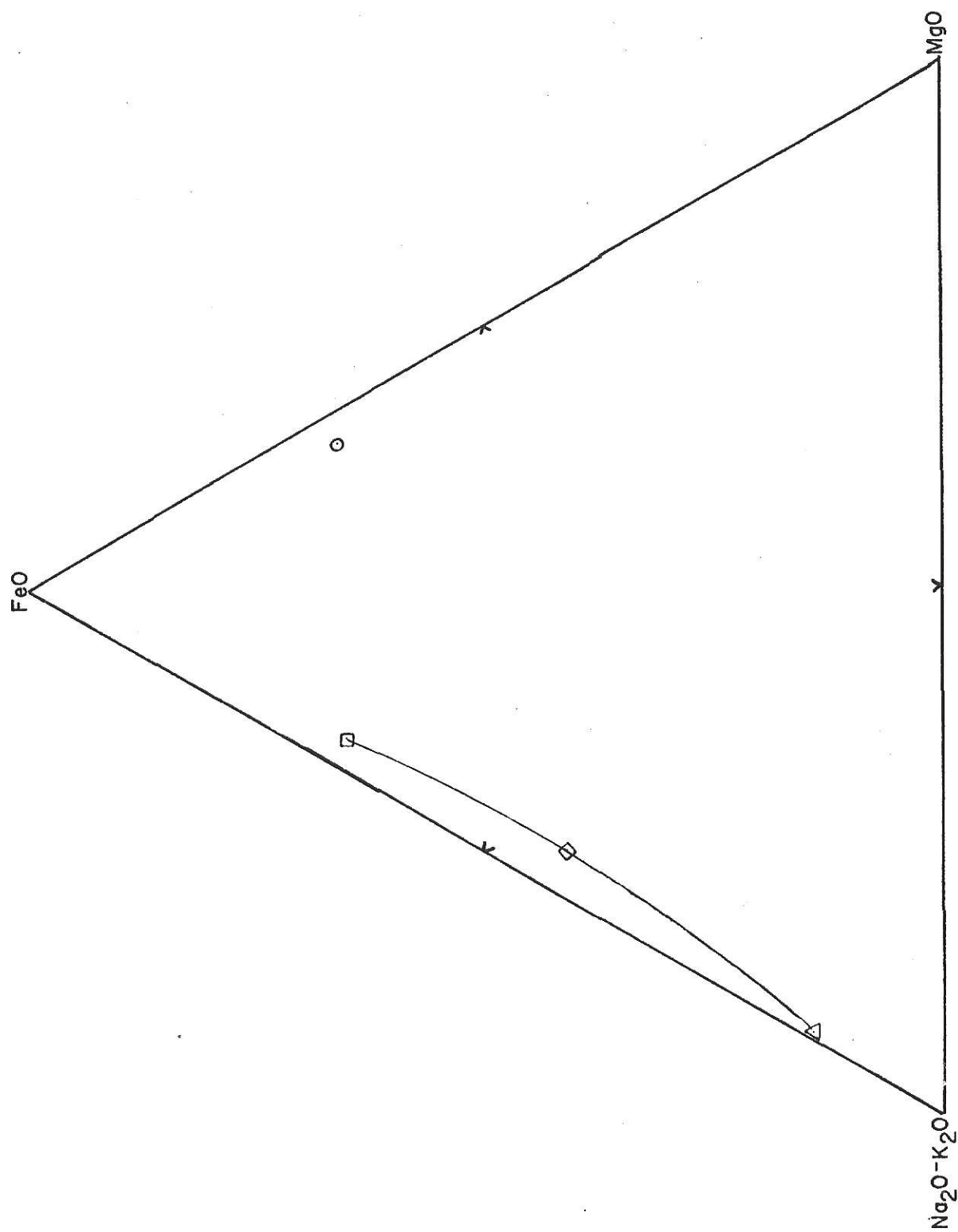


Figure 8. AFM diagram of Gem Park samples plotted in terms of mole per cent Fe, Mg, and Na+K for gabbro, GP-1g (O), pyroxenite GP-6 (□), pyroxenite, GP-3 (◇), and nepheline syenite pegmatite, GP-4 (Δ).

This is in agreement with Powell et al. (1966) who argued against the hypothesis of metasomatism of crustal rocks, sial-syntexis, for the origin of alkaline rocks associated with carbonatite complexes.

The carbonatites have higher Sr isotopic ratios (0.7036-0.7056, Table 3) than most alkaline rocks, but these can still be considered similar to those of the gabbro and pyroxenite within the limits of analytical precision. These initial Sr ratios are low enough to suggest an upper mantle source as hypothesized by Powell et al. (1966) who found the average initial Sr ratio for 21 carbonatites was 0.7035 ± 0.0003 .

This is considerably lower than the range of initial Sr ratios for most limestones, 0.707-0.711 (Powell et al., 1966). There is a small amount of overlap between the ratios for limestones and carbonatites as a few limestones have initial Sr ratios as low as 0.7055, and a few carbonatites have initial ratios as high as 0.7075 (Faure and Powell, 1972).

The Gem Park carbonatite, GP-9a&b, has a higher initial Sr ratio than the other carbonatites and alkaline rocks (Table 3). It is comparable to a carbonatite from nearby McClure Mountain, Colorado (Fenton and Faure, 1970) and to a carbonatite from Rocky Boy, Montana (Powell et al., 1966; Table 4). There is no petrographic evidence of contamination in carbonatite, GP-9a&b. However, its higher initial Sr ratio may indicate either contamination with a Sr-rich crustal rock having a typical crustal Sr isotopic ratio of 0.719 (Faure and Powell, 1972), or a slightly different mantle source from that which produced the other Gem Park carbonatites.

The nepheline syenite pegmatite has an initial Sr ratio of 0.7038

which is slightly higher than those of the Gem Park alkaline rocks (Table 3). It is comparable to the initial Sr ratio given for a nepheline syenite from Magnet Cove, Arkansas (Powell et al., 1966). Assimilation of a Sr-rich crustal rock with a typical crustal Sr isotopic ratio of 0.719 (Faure and Powell, 1972) could explain the higher initial ratio of the nepheline syenite pegmatite assuming the initial Sr ratio was originally similar to that of the gabbro and pyroxenite.

Rare Earth Elements

Derivation of Models.--In the Gem Park complex, there is a general trend of enrichment in the light REE and increase in total REE abundance from (GP-6) pyroxenite to the gabbros to the nepheline syenite pegmatite to (GP-3) pyroxenite to the carbonatites.

The equations derived by Haskin et al. (1970) were used to generate the REE models in this study. Haskin et al. (1970) have simplified the equations originally derived by Gast (1968) and Shaw (1969) that deal with trace element fractionation during partial melting and fractional crystallization. They assumed that the mineral proportions remain the same and that the distribution coefficient for the trace element in question remains constant throughout the entire process.

The derived phase in fractional crystallization is the solid phase (crystals) and the average concentration for the system refers to the REE concentration of the melt before crystallization starts. In partial melting, the derived phase would be the liquid phase (melt), and the

average concentration for the system would be the REE concentration of the initial source rock before it began to melt.

For fractional crystallization, equation (2), $C_{D,REE}/C_{A,REE} = \left[1 - (1-x)^{D^{REE}} \right] / x$, from Haskin et al. (1970) may be used to generate the REE distribution of the crystallizing phase. The ratio, $C_{D,REE}/C_{A,REE}$, stands for the average concentration of the total amount of the derived phase to the average concentration for the system for a particular REE. In the equation, x is the fraction of completion of the process (per cent solidified or melted) and D^{REE} refers to the distribution coefficient for a particular REE.

A distribution coefficient is defined as the ratio of the equilibrium concentration for a REE in the derived phase to its equilibrium concentration in the residual phase (Haskin et al., 1970). The distribution coefficients used in this investigation are listed and referenced in Table 7 and graphed in Figure 9.

The residual phase for a fractional crystallization process can be calculated using equation (1) from Haskin et al. (1970): $C_{R,REE}/C_{A,REE} = (1-x)^{D^{REE}-1}$. The ratio, $C_{R,REE}/C_{A,REE}$, is the average concentration of the residual phase for a certain REE divided by the average concentration of the system for a certain REE. Again, x refers to the fraction of completion of the process, and D^{REE} is the distribution coefficient for a particular REE.

In fractional crystallization, the concentration of the residual phase is the concentration of the melt after a particular mineral (minerals) crystallizes. For partial melting, the concentration of the residual phase

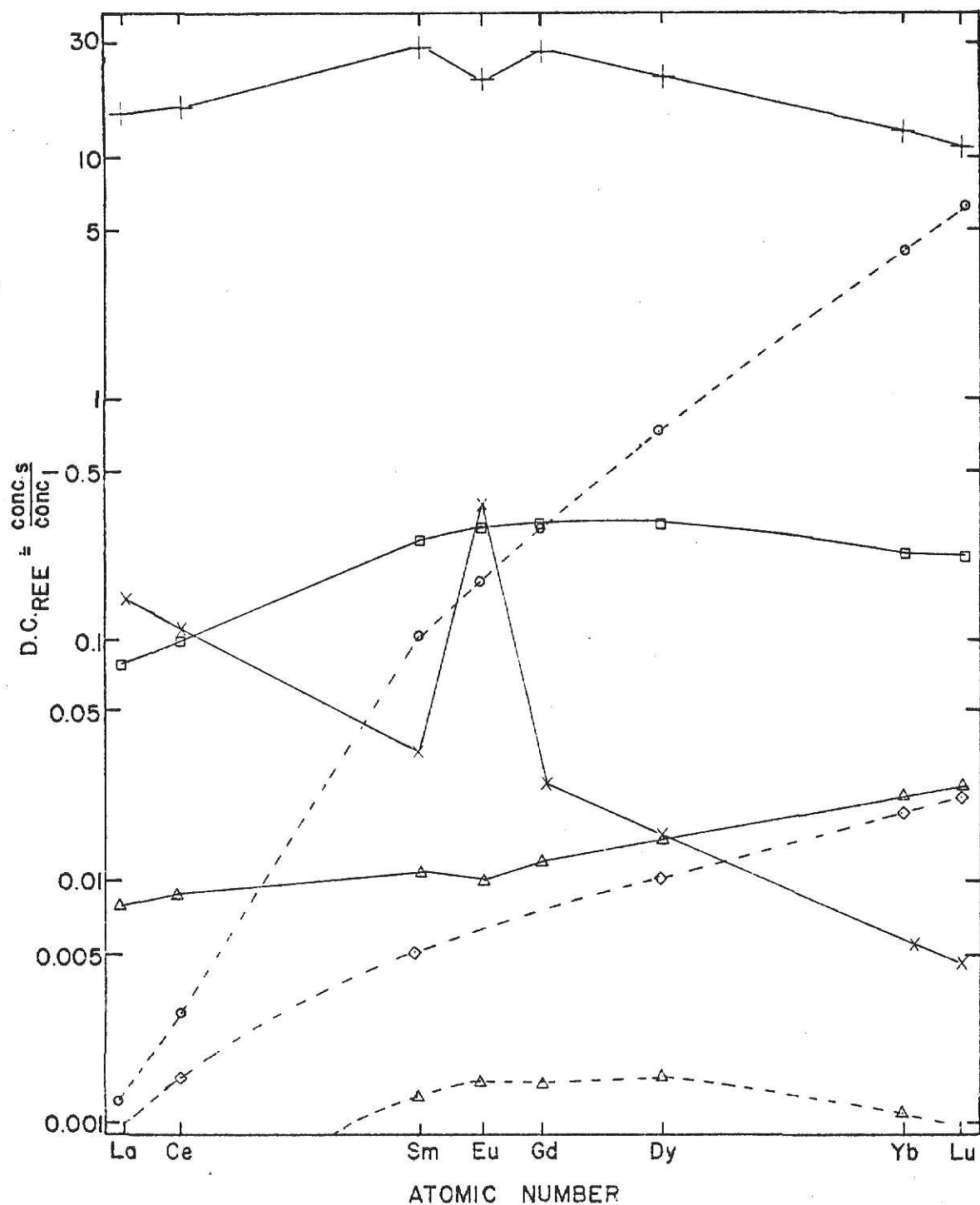


Figure 9. Distribution coefficients used in model calculations for the minerals apatite (+), clinopyroxene (□), plagioclase (X), olivine (Δ), garnet (○), and orthopyroxene (◇). Distribution coefficients used in partial melting models are indicated by dashed lines and those used in fractional crystallization models are shown by solid lines.

Table 7. The Distribution Coefficients (Mineral/Melt Ratios) Used for Model Calculations

Mineral; Reference	La	Ce	Sm	Eu	Gd	Dy	Yb	Lu
<u>Partial Melting</u>								
Olivine (1)	0.0003*	0.0005	0.0013			0.0016	0.0011	0.00098*
Clinopyroxene (1)	0.08*	0.096	0.261			0.313	0.227	0.2265*
Orthopyroxene (1)	0.00086*	0.0014	0.0049			0.01	0.0192	0.022*
Garnet (1)	0.00125*	0.0029	0.1065			0.788	4.199	6.45*
<u>Fractional Crystallization</u>								
Olivine (1)	0.008*	0.009	0.011	0.010	0.012		0.023	0.025*
Clinopyroxene (1)	0.08*	0.096	0.261	0.260	0.275		0.227	0.2265*
Apatite (2)	15.0*	18.0	29.0	21.0	28.0*		13.0	11.0*
Plagioclase (3)	0.15*	0.113	0.035	0.392	0.026		0.006	0.0046*

*Values by interpolation.

(1) Kay and Gast (1973), from Schnetzler and Philpotts (1970)

(2) Nagasawa (1970)

(3) Schnetzler and Philpotts (1970)

is the solid concentration after it has undergone anatexis.

Formation of the Alkaline Rocks.--Rock (1976) discussed the rarity of alkaline rock complexes containing both gabbroic rocks with calcic plagioclase and magmatic carbonatites. He hypothesized that an alkali basalt magma may be parental to both rock types. The gabbroic rocks would be derived from normal differentiation under low CO₂ pressure and the carbonatitic rocks would be formed by suppression of plagioclase crystallization under high pressures of CO₂ that produce by pyroxene fractionation a "secondary parental" olivine-poor nephelinitic magma.

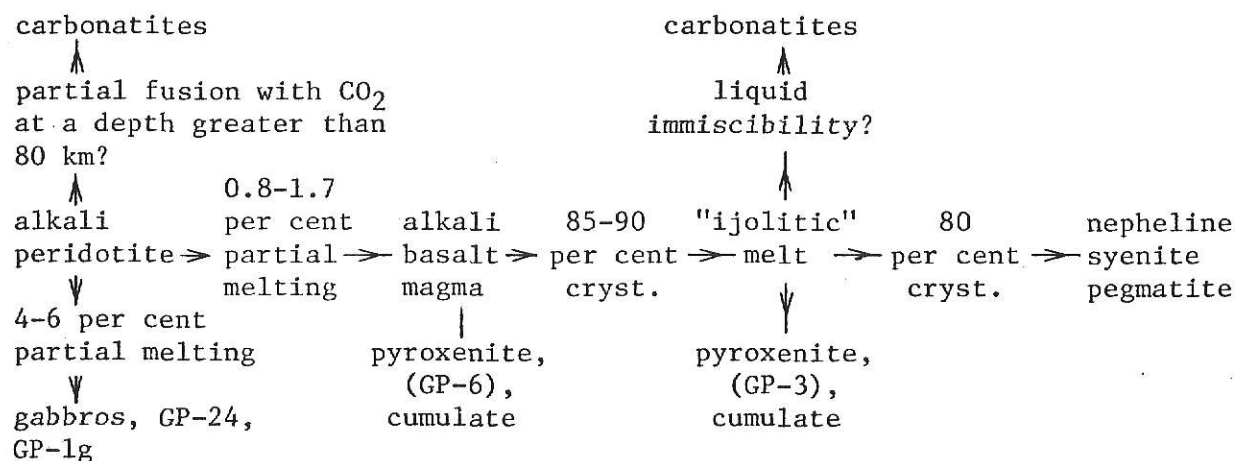
He cited Gem Park as one of only two carbonatite complexes of the 320 described (Heinrich, 1966) where a real genetic association between plutonic calcic plagioclase-bearing and carbonatitic rocks appears to exist. However, Rock believes that whatever process normally controls the antipathy of this association has been overcome here by abnormal amounts of fluorine. This casts doubt upon the genetic relationships of feldspar-bearing silicate rocks to carbonatite at Gem Park.

In the following discussion, it will be shown that the REE contents of all the rock types in the Gem Park complex excluding the gabbros can be derived as either cumulates or residual melts from a hypothetical alkali basalt parent magma found by 0.8-1.7 per cent partial melting of peridotite in the upper mantle.

The carbonatites could have formed either by partial fusion of the same peridotite with CO₂ at a depth greater than 80 km (Wyllie and Huang, 1976), or as immiscible liquid fractions from a hypothetical ijolitic

melt which formed as a residual liquid from the hypothetical alkali basalt magma (Cullers et al., 1976).

The gabbros are not related as a cumulate or residuum to the liquid line of descent from the hypothetical alkali basalt to the residual nepheline syenite liquid. However, the gabbros could have formed by further melting (4-6 per cent) of the same peridotite that produced the hypothetical alkali basalt magma. The following flow diagram summarizes the hypothetical relations of all the rocks in the complex:



Gabbros.--REE distributions for Gem Park gabbros, GP-1g and GP-24, are in Figure 4. By using the trace element models derived by Gast (1968), Kay and Gast (1973), and Haskin et al. (1970), for the generation of alkali basalt magmas by a small degree of partial melting of upper mantle peridotite, a range of compositions encompassing that of the gabbro, GP-24, can be calculated (Fig. 10).

The initial REE concentration of the alkali peridotite is assumed to be 2.3 times the chondritic REE values (Haskin et al., 1968). If the

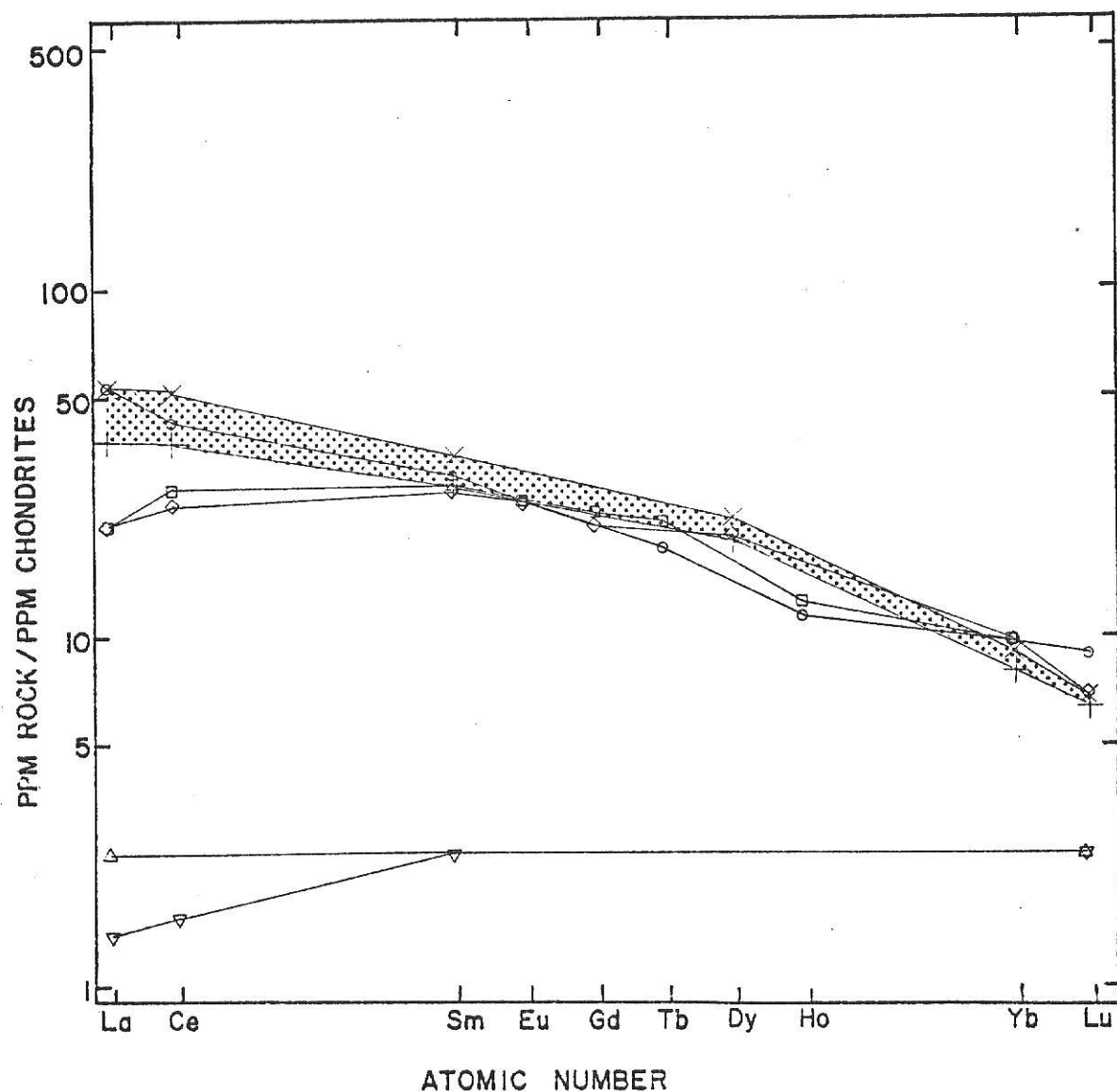


Figure 10. Model for the formation of the Gem Park gabbros by 4(x)-6(+)-6(+) per cent partial melting of peridotite (55 per cent olivine, 25 per cent orthopyroxene, 15.5 per cent clinopyroxene, 4.5 per cent garnet) in the upper mantle having an initial REE content (Δ) of 2.3 times the chondritic values to form gabbro, GP-24 ($\circ$). Gabbro, GP-1g ($\square$), was formed by the same partial melting model ($\diamond$) except its peridotite source was depleted in the light REE, i.e., La = 1.3 and Ce = 1.5 times the chondritic values (∇).

mineralogy of the peridotite is 55 per cent olivine, 25 per cent orthopyroxene, 15.5 per cent clinopyroxene, and 4.5 per cent garnet as suggested by Kay and Gast (1973) in their model for the generation of alkali basalts, a range of REE distributions similar to gabbro, GP-24, is produced by 4-6 per cent partial melting of this peridotite (Fig. 10).

However, gabbro, GP-1g, does not fit in this model because of its anomalous depletion in the light REE (Fig. 10). It is impossible to generate the light REE contents of gabbro, GP-1g, by the partial melting model of mantle peridotite as described above for gabbro, GP-24. If it assumed that the source peridotite for gabbro, GP-1g, had the same mineralogic composition as the source peridotite for gabbro, GP-24, but was depleted in initial REE content for only the light REE, i.e., La is 1.3 and Ce is 1.5 times the chondritic values for the REE, then a REE distribution similar to that of gabbro, GP-1g, is obtained (Fig. 10). The initial REE concentration for the middle and heavy REE is 2.3 times the chondritic values.

Pyroxenites and Nepheline Syenite Pegmatite.--Because it contains considerably more plagioclase (23 per cent) than the other Gem Park pyroxenites and shows cumulate textures, pyroxenite, GP-6, might be a cumulate from the gabbroic magma represented by gabbros, GP-24 and GP-1g. However, deriving pyroxenite, GP-6, as a cumulate in this manner proved to be impossible.

Therefore, the REE concentration of the melt that equilibrated with pyroxenite, GP-6, was approximated by substituting the REE concentrations

of GP-6 into the equation, $D.C._{REE} = \frac{C_s}{C_l} = \frac{C_{GP-6}}{C_l}$, and solving for C_l , the liquid concentration (Fig. 11). In this case, $D.C._{REE}$ is the average of the distribution coefficients for the cumulus phases in equilibrium with the melt ($D.C._{REE} = D.C._{ol} \times 5 \text{ per cent olivine} + D.C._{plag.} \times 10 \text{ per cent plagioclase} + D.C._{cpx} \times 85 \text{ per cent clinopyroxene}$).

Petrographic examination shows that only 10 per cent of GP-6, pyroxenite's modal plagioclase can be considered cumulate. The REE concentrations of pyroxenite, GP-6, support this. Plagioclase preferentially incorporates Eu; therefore, significant plagioclase crystallization (greater than 15 per cent) will produce a positive Eu anomaly in a cumulate. However, the pyroxenite, GP-6, has no such positive Eu anomaly.

The remaining 13 per cent interstitial plagioclase in pyroxenite, GP-6, plus about 2 per cent kaersutite probably results from crystallization of intercumulus melt. A small per cent of contamination of the cumulate pyroxenite, GP-6, with this trapped primary melt having a high REE content will raise the REE content of the cumulate considerably. The range of melt REE concentrations estimated to be in equilibrium with the whole rock pyroxenite would therefore be too high.

The REE contents of the cumulate and the hypothetical melt with which it equilibrated can be adjusted for the 15 per cent trapped intercumulus melt by using an equation which can be derived as follows. The observed REE concentration for a particular REE in the cumulate, C_{REE} , is equal to 85 per cent times the concentration of the solid plus 15 per cent times the concentration of the liquid, i.e., $C_{REE} = 0.85(\text{conc}_s) + 0.15(\text{conc}_l)$. If x = ppm contributed by the solid, then $y - x$ = ppm contributed by the liquid (y is the concentration for a particular REE). Therefore,

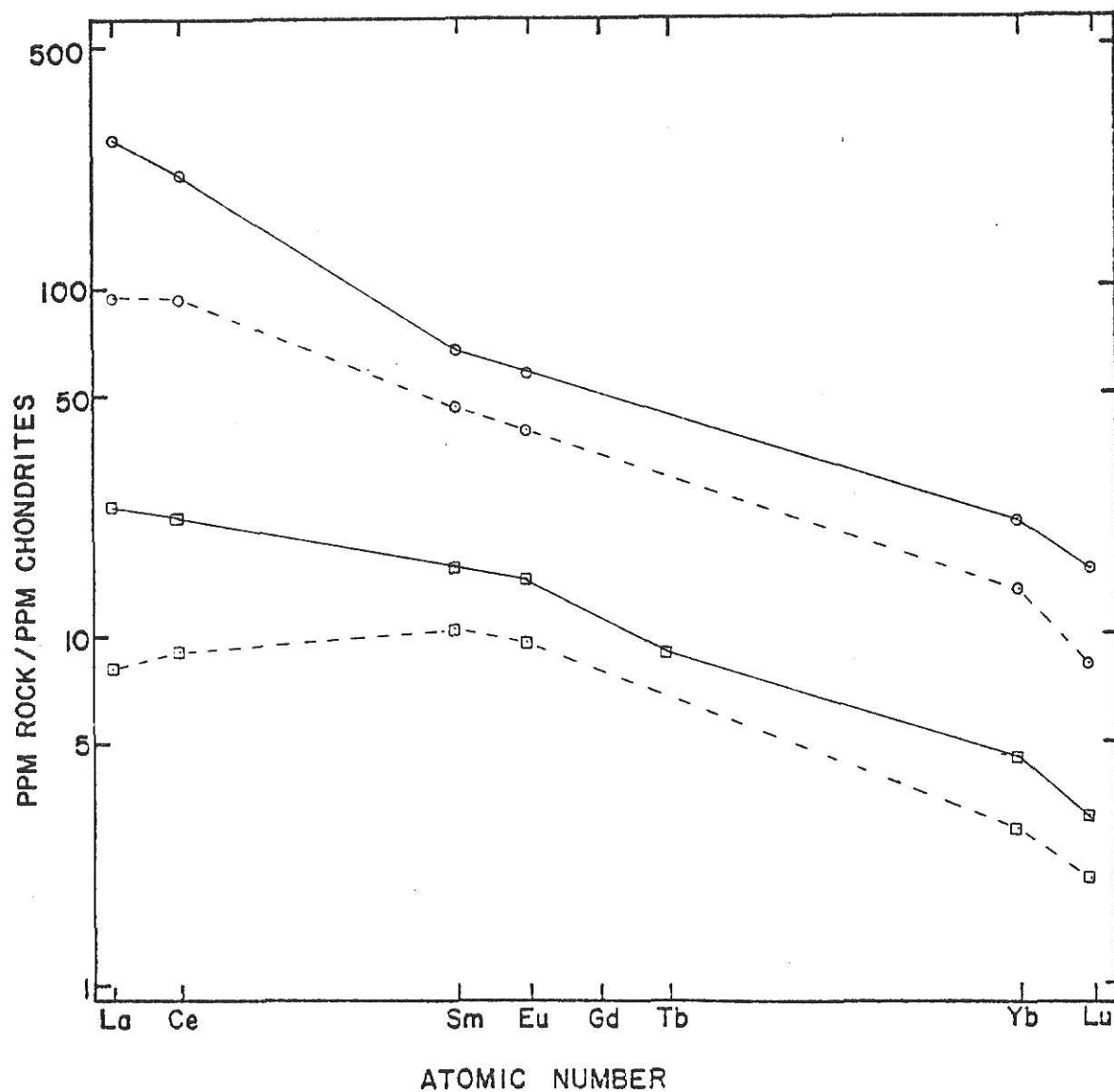


Figure 11. REE distributions for pyroxenite, GP-6 (□), and the hypothetical melt with which it equilibrated (○) before adjustment for 15 per cent trapped interstitial primary melt. The adjusted REE concentrations for pyroxenite, GP-6 (□), and its hypothetical melt (○) are indicated by dashed lines.

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by algebraic substitution, $\text{conc}_s = \frac{x}{0.85}$ (cumulate REE concentration) and $\text{conc}_l = \frac{y-x}{0.15}$ (melt REE concentration).

Because the distribution coefficient for a particular REE (D.C._{REE}) is defined as the equilibrium concentration of the solid/ the equilibrium concentration of the liquid, the formula, $\text{D.C.}_{\text{REE}} = \frac{\text{conc}_s}{\text{conc}_l} = \frac{\frac{x}{0.85}}{\frac{y-x}{0.15}}$, can be used to approximate the adjusted REE concentration of the cumulate and the hypothetical melt with which it equilibrated (Fig. 11).

The resulting REE distribution for the hypothetical melt with which pyroxenite, GP-6 equilibrated falls close to the range of concentrations for alkali basalts (Fig. 12; Kay and Gast, 1973). Thus, the pyroxenite, GP-6, can be considered a cumulate from an alkali basalt magma.

In their trace element model for alkali basalt genesis, Kay and Gast (1973) stated that the alkali basalts, U-Hill-1 and K-12, can be generated by a small degree of partial melting (0.8-1.7 per cent) in an upper mantle composed of alkali peridotite (55 per cent olivine, 25 per cent orthopyroxene, 15.5 per cent clinopyroxene, and 4.5 per cent garnet) which had an initial REE concentration 1.9 times the chondritic values. This model is consistent with the generation of the REE contents for the hypothetical alkali basalt melt at Gem Park.

If this hypothetical alkali basalt melt crystallized phases such as olivine, plagioclase and clinopyroxene in the proportion 5:10:85, respectively, when the alkali basalt melt is 85-90 per cent crystallized, the residual liquid would have a REE concentration similar to natural ijolites (Fig. 13).

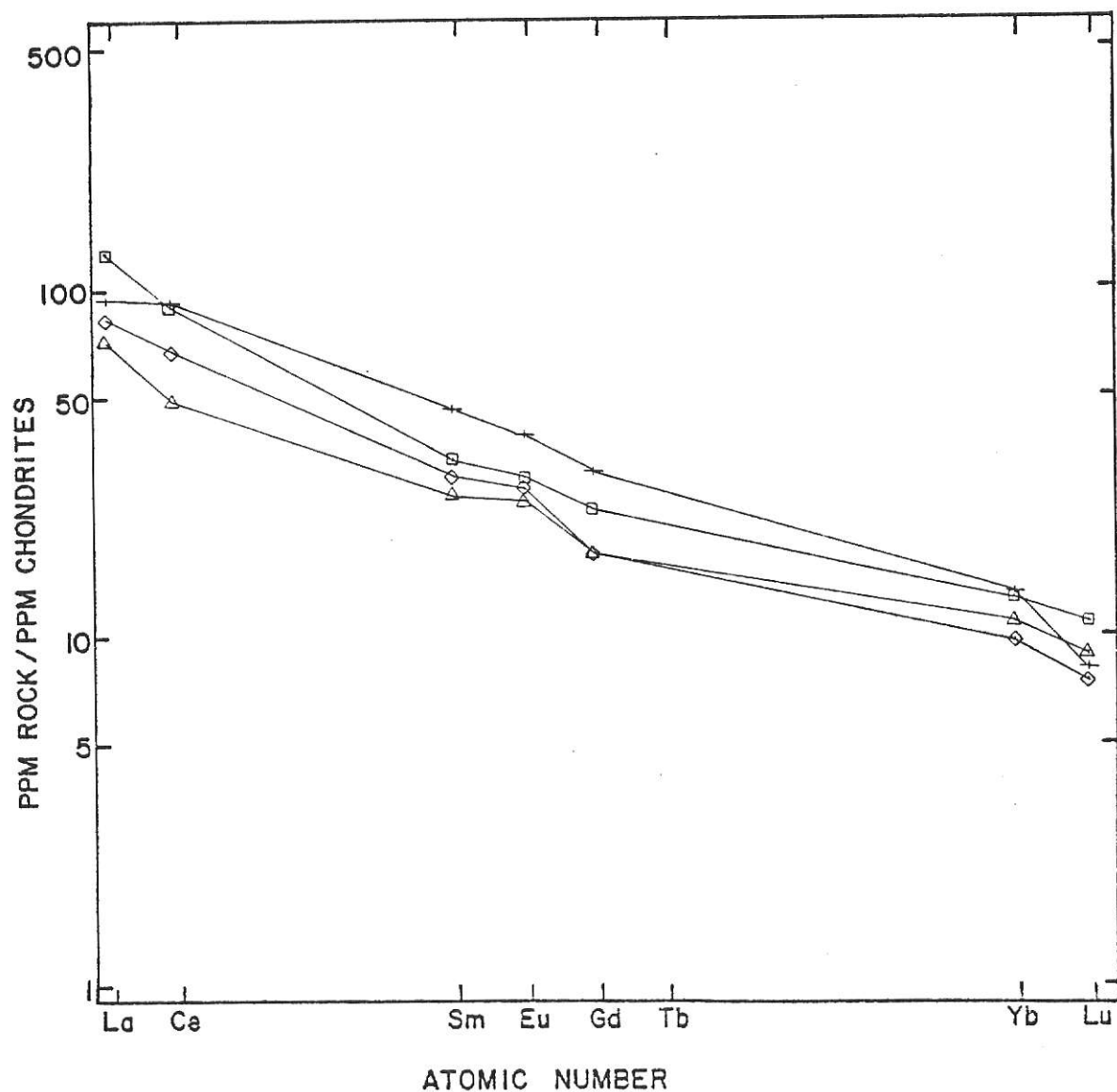


Figure 12. REE distributions for the hypothetical melt with which pyroxenite, GP-6, equilibrated (+) compared to a range of alkali basalt REE concentrations, U-Hill-1 (□), K12 (◇), 04 (△), (Kay and Gast, 1973).

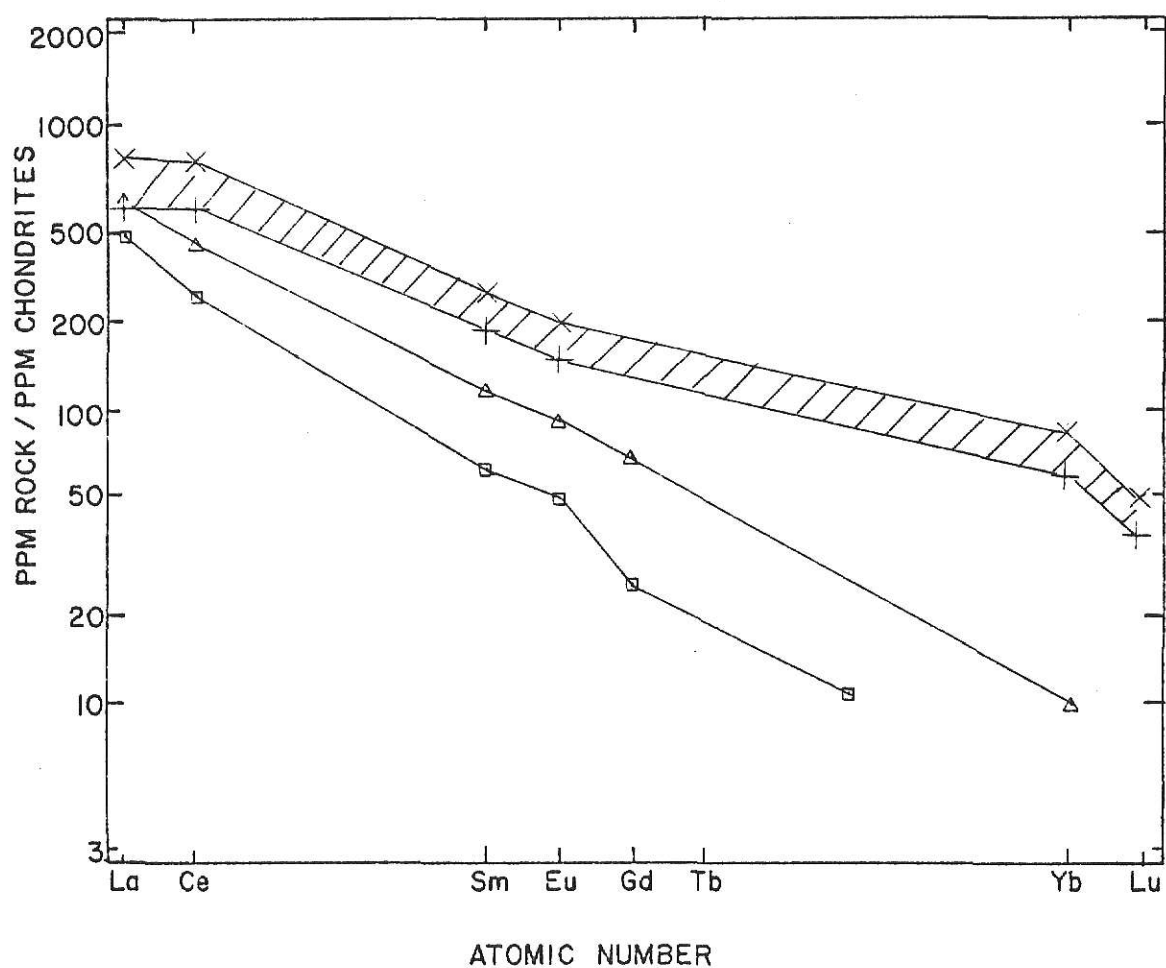


Figure 13. A comparison of the REE concentrations for the residual liquid from the hypothetical alkali basalt melt after 85 (+) - 90 (x) per cent crystallization of olivine:plagioclase:clinopyroxene::5:10:85 with the REE distributions of natural ijolites from Oka (A-14-5, □) (Eby, 1975) and Seabrook Lake (Δ) (Cullers et al., 1976).

The pyroxenite, GP-3, has a considerably higher REE abundance than the pyroxenite, GP-6 (Fig. 5). The REE concentrations could not be derived as a cumulate from an alkali basalt melt because the REE concentrations are higher than those of most alkali basalts (Fig. 5).

Pyroxenite, GP-3, has a higher $\frac{\text{Na+K}}{\text{Fe}}$, 0.24, and $\frac{\text{Na+K}}{\text{Mg}}$, 18.88, than does pyroxenite, GP-6 (0.12 and 0.29, respectively). This suggests that pyroxenite, GP-3, could have equilibrated with a more "fractionated alkali basalt" or an ijolitic melt than did GP-6. The presence of only about one per cent interstitial plagioclase is also consistent with crystallization from an ijolitic melt.

The melt, with which pyroxenite (GP-3) equilibrated, can be approximated by using the equation, $\text{D.C.}_{\text{REE}} = \frac{\text{conc}_s}{\text{conc}_1} = \frac{\text{conc}_{\text{GP-3}}}{\text{conc}_1}$, as was done for pyroxenite, GP-6. In this case, D.C._{REE} would be the distribution coefficient for clinopyroxene because that is the only cumulus phase. The resulting hypothetical melt REE distributions are higher than those of natural ijolites (Fig. 14).

However, pyroxenite, GP-3, is petrographically very similar to other Gem Park pyroxenites, i.e., sample GP-5 (Appendix D), except for a slight difference in the per cent of plagioclase. If it is assumed that up to 3 per cent interstitial plagioclase and about 2 per cent kaersutite represents trapped intercumulus primary liquid in pyroxenite, GP-3, the REE concentrations for cumulate pyroxenite, GP-3, and its hypothetical ijolitic melt can be adjusted in the same manner as described for pyroxenite, GP-6, and its hypothetical alkali basalt melt (Fig. 14).

After adjustment for approximately 5 per cent trapped intercumulus

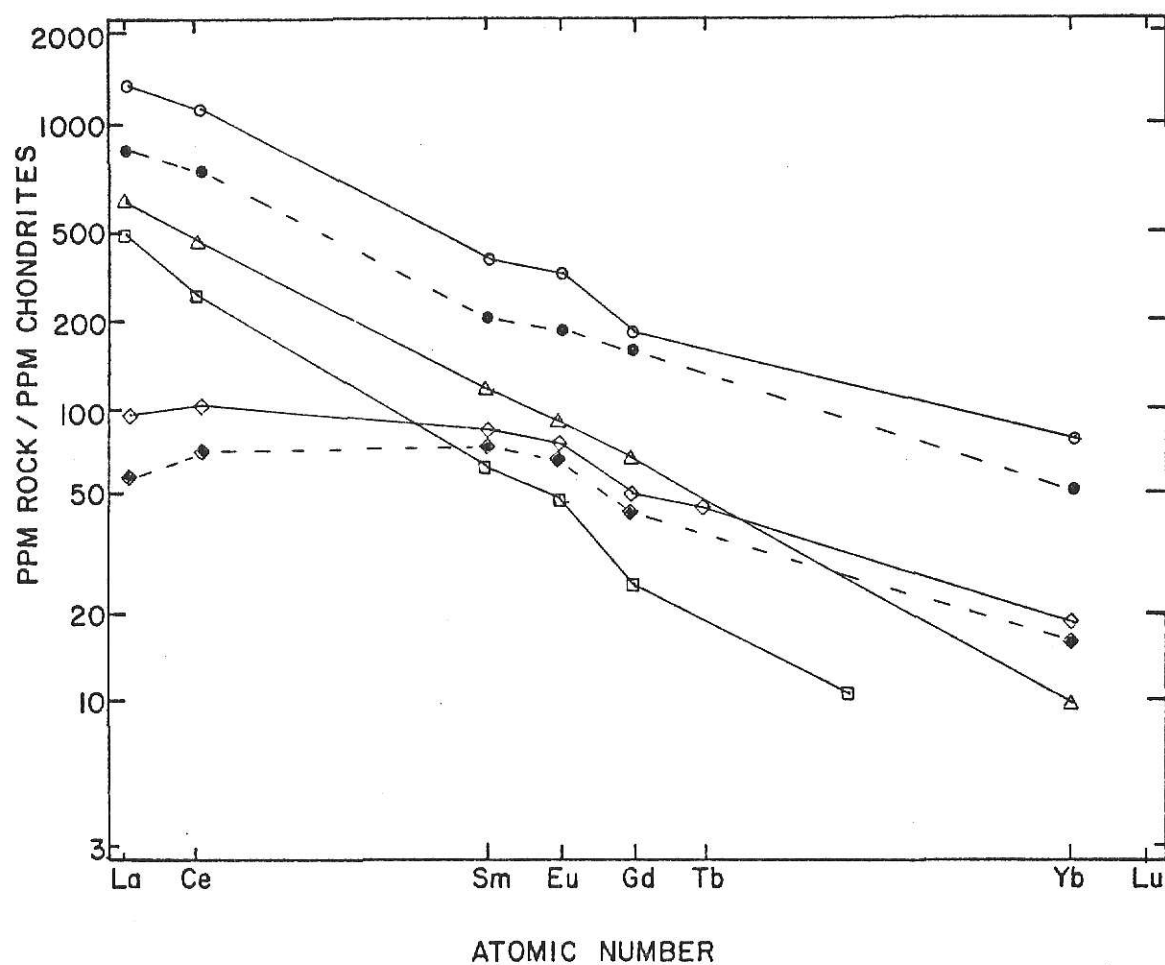


Figure 14. A comparison of the hypothetical ijolitic melt with which pyroxenite, GP-3 ($\diamond$), equilibrated with REE distributions for natural ijolites from Oka (A-14-5, $\square$) (Eby, 1975) and Seabrook Lake ($\triangle$) (Cullers et al., 1976) before ($\circ$) and after ($\bullet$) adjustment for 5 per cent trapped intercumulus melt. The adjusted REE concentration for pyroxenite, GP-3 ($\blacklozenge$) is also given.

melt (3 per cent plagioclase + 2 per cent kaersutite), the REE distribution for the hypothetical ijolitic melt with which pyroxenite, GP-3, equilibrated is closer to those of natural ijolites (Fig. 14). This hypothetical ijolitic melt is also within the range of residual liquid REE concentrations calculated from the hypothetical alkali basalt with which pyroxenite, GP-6, equilibrated (Fig. 15).

Therefore, the cumulate pyroxenite, GP-3, possibly equilibrated with an ijolitic melt which was the residual liquid that resulted from 85-90 per cent crystallization of olivine, plagioclase, and clinopyroxene from the hypothetical alkali basalt melt.

In comparison to known REE distributions for ijolites from such complexes as Oka (Eby, 1975) and Seabrook Lake (Cullers et al., 1976), the hypothetical ijolitic melt at Gem Park does not show as great a depletion in the heavy REE (Fig. 14).

The lack of outcrop of ijolite at Gem Park can be explained in two ways: 1) The ijolite mass may be located at depth with the unexposed carbonatite plug in the central part of the complex as is suggested by the structural evidence previously discussed. This is a common association in most carbonatite complexes (Tuttle and Gittins, 1966; Heinrich, 1966). 2) Because the ijolite is the residual melt of the hypothetical alkali basalt melt after 85-90 per cent crystallization it would have a very small volume. It may be completely used up in the formation of pyroxenite, GP-3, and the nepheline syenite pegmatite.

Because of its pegmatitic texture and very small outcrop area, the nepheline syenite pegmatite is considered to be a late, small intrusive in the Gem Park sequence. The ijolitic melt that crystallized pyroxenite,

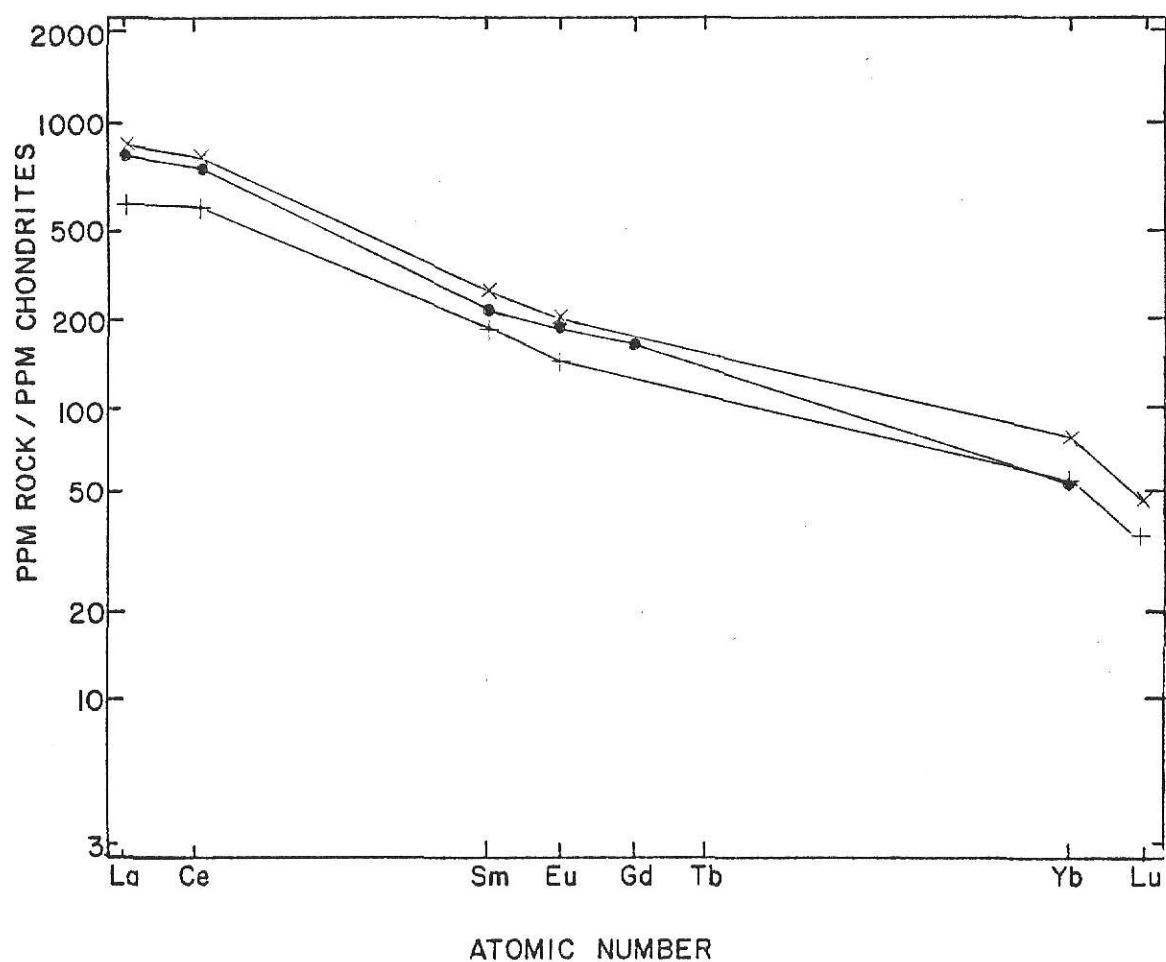


Figure 15. A comparison of the REE distributions for the hypothetical ijolitic melt that equilibrated with cumulate pyroxenite, GP-3 (●), with the range of residual liquid REE concentrations from the alkali basalt magma 85(+) - 90(X) per cent crystallization .

GP-3, as a cumulate could also have produced the nepheline syenite pegmatite as the residual melt. Experimental petrology supports such an origin for nepheline syenite magmas.

Bailey and Schrairer (1966) postulated that partial melting of alkaline basalt in deep crust or upper mantle will produce alkalic syenites and related magmas. They found that precipitation of calcic plagioclase tends to leave alkali silicates in the residual liquid. This means that any rocks with diopside in the norms, e.g., GP-6 and GP-3, pyroxenites, would have compositions which would allow the plagioclase effect to work.

Thus, equilibration of calcic plagioclase-rich pyroxenite, GP-6, with an alkali basalt melt would enrich the residual liquid (the ijolitic melt) in the alkalies. The subsequent equilibration of pyroxenite, GP-3, with the ijolitic melt would create a residual liquid enriched in the alkalies, i.e., the nepheline syenite pegmatite.

If the residual liquid after 80 per cent crystallization of phases such as apatite and clinopyroxene in the proportion 10:90, respectively, from the hypothetical ijolitic melt is calculated, its REE content is similar to that of the nepheline syenite pegmatite, GP-4 (Fig. 16). About 4 per cent apatite is common in Gem Park pyroxenites similar mineralogically to GP-3 which equilibrated with the ijolitic melt (Parker and Sharp, 1970). Therefore, it is possible in the formation of the nepheline syenite pegmatite as a residual liquid, pyroxenitic phases containing about 10 per cent apatite may have crystallized from the hypothetical ijolitic melt.

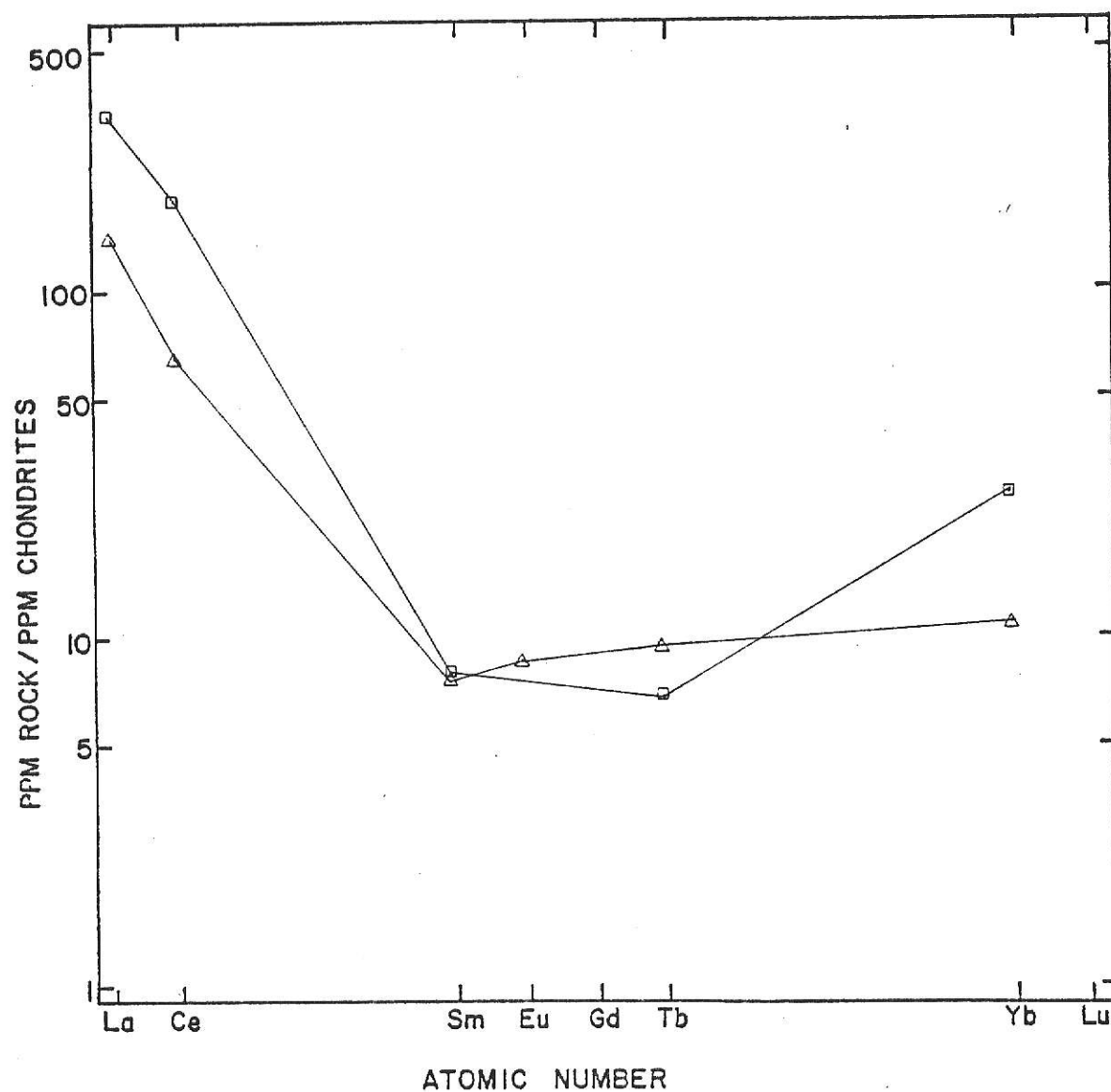


Figure 16. Model for the formation of the nepheline syenite pegmatite, GP-4 (Δ), as the residual liquid from the ijolitic melt after 80 per cent crystallization of phases such as apatite and clinopyroxene in the proportion of 10:90 (□).

Carbonatites.--Two main hypotheses explain the origin of carbonatites:

1. Carbonatite magmas are primary. Reaction of these primary carbonatite magmas in the upper mantle or crust forms the associated alkaline rocks (Dawson, 1964, 1966, 1967; von Eckermann, 1948; Holmes, 1952; Koster van Groos, 1975).

2. Carbonatite magmas have a derived origin. They are formed through the differentiation of an alkaline ultrabasic magma (carbonated alkali peridotite, nephelinite, ijolite), either as a residual product of fractional crystallization (Wyllie and Haas, 1965, 1966; King and Sutherland, 1960; Watkinson, 1970; Watkinson and Wyllie, 1971) or as an immiscible liquid fraction from the parent melt (Mitchell and Brunfelt, 1975; Koster van Groos and Wyllie, 1966, 1968, 1973; Wyllie and Huang, 1976; Cullers et al., 1976).

Primary Melt.--Low initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios for the Gem Park alkaline rocks and carbonatites except for carbonatite, GP-9a&b, suggest a source in the upper mantle which eliminates the possibility of the first hypothesis being true. The similarity of the initial Sr ratios indicates that the rocks are probably consanguinous. Thus, there is no evidence at Gem Park to support the formation of the alkaline rocks by the reaction of a primary carbonatite magma with crustal rocks. However, it is possible that carbonatite, GP-9a&b, may have assimilated a Sr rich crustal rock which would result in its higher initial Sr ratio.

Cullers et al. (1976) have shown that it is impossible to generate by direct partial melting of peridotites or eclogites the REE content of

the carbonatite from Seabrook Lake. They used peridotites and eclogites in their models with known distribution coefficients for the mineral phases.

Using the trace element models described by Gast (1968) and Kay and Gast (1973) for the formation of alkali-rich magmas by small degrees of partial melting (less than 5 per cent) of upper mantle peridotite and eclogite, Cullers et al. tried to generate REE distributions similar to those of carbonatites. They assumed a constant proportion of phases melted (Haskin et al., 1970) and the minimum distribution coefficients for an upper mantle mineralogy (Schnetzler and Philpotts, 1970).

The maximum light REE content they could generate is in Figure 17. It was calculated by assuming a 0.50 per cent melting of a source containing 49.5 per cent olivine, 49.5 per cent orthopyroxene, and 1 per cent garnet and having a light REE content 8-9 times chondrites and a heavy REE content 4 times chondrites. The resulting REE distribution closely approximates the middle and heavy REE contents of Gem Park carbonatites, GP-9a&b and GP-7b (Fig. 17). However, the content of the light REE for GP-7b is 1.8 times higher than those of the calculated model.

The amount of La in GP-9a&b is close to that of the model, but Ce is 1.3 times higher, that is, La is anomalously low for a carbonatite. GP-6b contains 1.9 times the amount of light REE and 2.1 times the amount of the middle REE than the model partial melt.

GP-8 is the only carbonatite that has a lower total REE abundance than the model. This is unusually low for a carbonatite. It might have

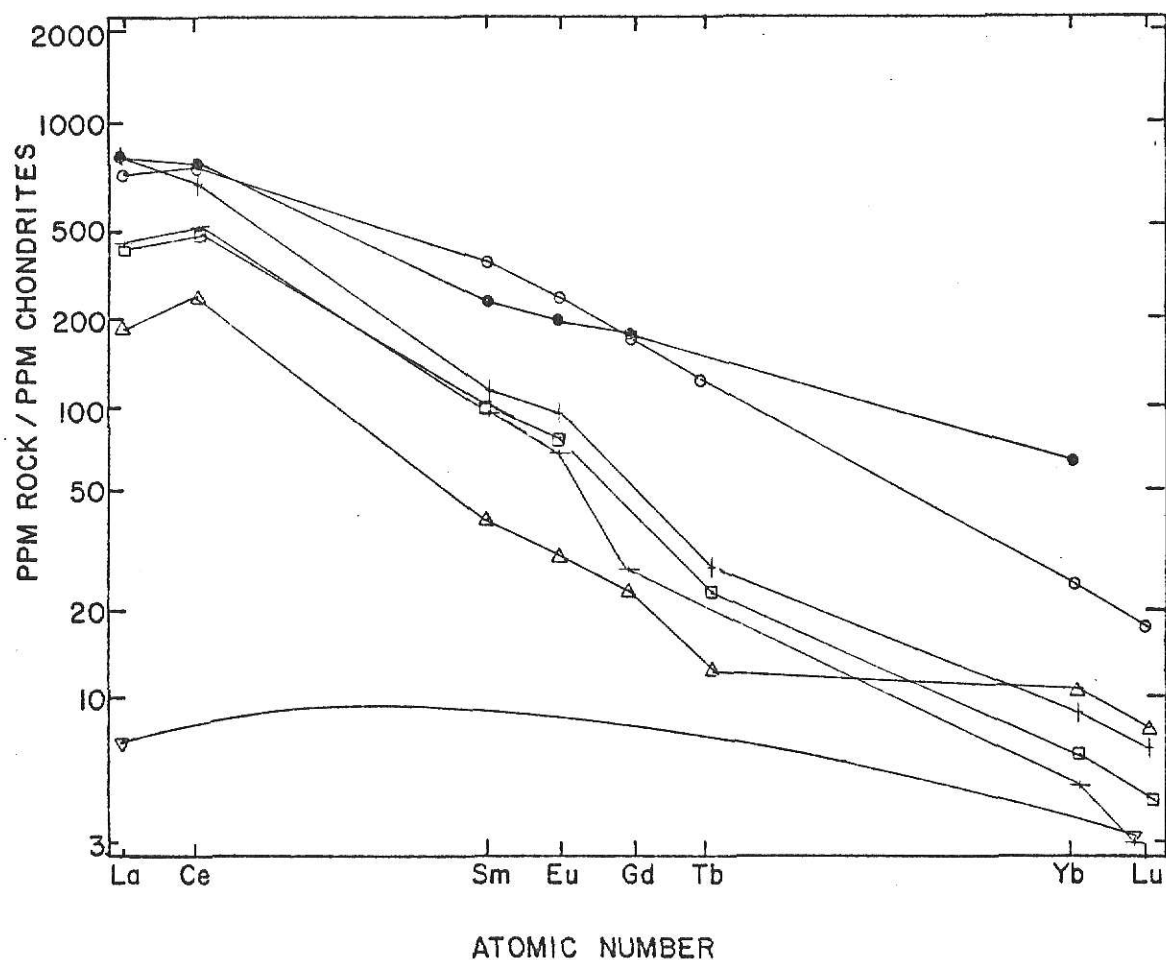


Figure 17. REE distributions for the Gem Park carbonatites, GP-6b (○), GP-7b (+), GP-9a&b (□), GP-8 (△), compared to the hypothetical ijolitic melt that equilibrated with pyroxenite, GP-3 (●), and the primary melt derived by Cullers et al. (1976) (▽) by 0.5 per cent partial melting of a source containing 49.5 per cent olivine, 49.5 per cent orthopyroxene, and 1 per cent garnet and having a light REE content 8-9 times chondrites and a heavy REE content 4 times chondrites (▽).

formed by partial melting of mantle peridotite or eclogite and has been further fractionated by CO_3 crystallization. Distribution coefficients for $\text{CO}_3(\text{s})-\text{CO}_3(\text{l})$ have not been experimentally determined but carbonate melts crystallize rapidly resulting in possible internal zoning and variations in REE content.

It can be concluded the light REE contents of Gem Park carbonatites, GP-6b, GP-7b, and GP-9a&b, cannot be produced directly by partial melting of mantle peridotites or eclogites, but the REE contents of carbonatite, GP-8, may have formed in this manner.

Koster van Groos (1975) proposed a different model for the primary origin of carbonatite. He hypothesized that in the mantle, especially under continental shields, carbonates may be partial or complete liquids of complex composition, containing in addition to CaO , MgO , FeO , and alkalis, the REE and other incompatible elements (Green and Ringwood, 1967). There must be a significant amount of H_2O dissolved in the carbonate also. Under certain conditions over a long period of time, this liquid will begin to concentrate.

The low viscosity and high pressure of the carbonate liquid may cause it to move upward rapidly. Because its density is lower than that of the surrounding silicate melt, the carbonatite magma may begin its upward movement before a large amount is concentrated, resulting in a magma of small volume.

At a higher level in the mantle, partial melting of the silicates to form a basaltic melt (Green, 1973) may be caused by the carbonatite melt. Reaction of the carbonatite melt with the silicate solid-liquid

assemblage would release CO_2 into a vapor phase and initiate the explosive activity commonly associated with carbonatite complexes. After the reaction, a silicate solid-liquid assemblage enriched in MgO , FeO , CaO , and alkalis would form. The magma would approach the composition of the urtite-ijolite-melteigite series of carbonatite complexes. The vapor phase, enriched in alkalis, could form fenitizing solutions at low temperatures.

Koster van Groos (1975) pointed out that this model may not be valid for all carbonatite occurrences. He believed that the most important condition for the formation of a carbonatite liquid is the CO_2 -rich environment at pressures high enough to stabilize carbonates. For carbonate liquids with high MgO contents, like those of Gem Park, he believed that pressures greater than those in the crust are required if the liquid coexists with or descends from a silicate liquid.

In terms of the REE concentrations, this model could be consistent with those of Cullers et al. (1976) and Wyllie and Huang (1976). This will be discussed later under "liquid immiscibility".

Fractional Crystallization.--In the model already presented for the formation of the Gem Park complex, the carbonatites cannot be residual products of the differentiation trend that produced the ijolitic magma if it is assumed that the nepheline syenite pegmatite is the residual liquid. Mitchell and Brunfelt (1975) and Cullers et al. (1976) have shown that for the Fen complex, Norway and the Seabrook Lake complex, Ontario, extensive fractional crystallization of an ijolitic magma to produce the high REE contents of residual carbonatites is not reasonable because significant amounts of sphene and apatite are in the ijolites.

Both sphene and apatite tend to concentrate the REE and have distribution coefficients much greater than one (Fig. 9; Table 5).

The REE concentration in the Gem Park ijolitic melt is within the range of those of the carbonatite samples (Fig. 17). Because an ijolitic melt is hypothetical and does not crop out, it is assumed to have a mineralogic composition similar to other ijolites (Cullers et al., 1976; Eby, 1975).

Because three of the Gem Park carbonatites have REE concentrations close to that of the ijolitic melt, it is improbable based on the above discussion that they are residual melts from the ijolite. In fact, the carbonatite, GP-6b, with the highest REE concentration has the largest percentage of apatite (about 4 per cent). If it were a residual product of fractional crystallization of the ijolite, it should have the lowest REE distribution of the four samples.

The high apatite content of these carbonatites may represent cumulate apatite from internal fractionation. This is supported in thin section because the apatite tends to be concentrated in lenses within the carbonatite. This would explain why the carbonatite with the greatest percentage of apatite (GP-6b) has the highest REE content.

The other three carbonatites that are lower in REE content do not contain significant amounts of apatite (less than one per cent).

Liquid Immiscibility.--The formation of carbonatite magmas as immiscible phases from their parent melt has been demonstrated experimentally in different systems by Koster van Groos and Wyllie (1964, 1966,

1968, 1973). Koster van Groos (1975) has shown also that the distribution of Sr between coexisting silicate and carbonate liquids at elevated pressures and temperatures supports the formation of alkaline-carbonatite complexes by liquid immiscibility.

Sr fractionates strongly toward both liquid phases of a carbonate liquid-silicate liquid-solid assemblage but the crystallizing phases are depleted in Sr. Because the alkaline igneous rocks associated with carbonatites are not significantly depleted in Sr compared with the carbonatites, Koster van Groos concluded that alkaline-carbonatite complexes are formed by a pair of immiscible liquids rather than a late stage fractionation process.

Mitchell and Brunfelt (1975) in their study of the Fen complex, Norway, suggested that a mantle-derived nephelinitic magma through liquid immiscibility produced a lamprophyric and a carbonatitic magma. By fractional crystallization, the lamprophyric magma differentiated to form the alkaline rocks of the complex.

Cullers et al. (1976) presented new evidence in support of liquid immiscibility. They used their determinations of REE partitioning between carbonate-rich ocelli and host lamprophyres from the Callander Bay, Ontario, complex as models for the REE behavior in coexisting carbonate-silicate liquids.

The REE concentration in the carbonate ocelli from Callander Bay is two to three times greater than in the lamprophyre. This is consistent with the total REE content being greater in the carbonatites from complexes such as Seabrook Lake and Oka than in the coexisting ijolites and okaites,

respectively (Eby, 1975). Carbonate liquids preferentially incorporate the REE in all these cases; thus, a comagmatic-immiscibility origin is suggested for these carbonatite-alkaline rock associations.

Cullers et al. (1976) also stated that there is a discrepancy in the La/Lu ratio for carbonatites that are separated physically from their coexisting ijolitic melts and carbonatite melts coexisting with lamprophyric magmas. The La/Lu ratios of the former carbonatites tend to be higher than those of the ijolites, but the La/Lu ratios for the latter carbonatite melts are similar or lower than the La/Lu ratios of the lamprophyric magma.

This was explained experimentally by Mineyev et al. (1966) as the result of greater volatile transport of the heavy REE relative to the light REE by volatile transport as CO_3^{-2} or F^- complexes out of the carbonatite melts than from the separated silicate melts. Cullers et al. (1970, 1973) have shown that the REE do not move very readily out of silicate melts in which there is little complexing of CO_3^{-2} or F^- .

Wyllie and Huang (1976) have presented another model for carbonatite formation based on experimentally determined CO_2 solubilities in mantle magmas. At depths to 80 km, the solubility of CO_2 in mantle magmas is less than about 5 weight per cent, but it increases abruptly to about 40 weight per cent at 80 km and deeper. They suggested that fusion of peridotite with CO_2 at depths deeper than 80 km will produce basic magmas that become more SiO_2 -undersaturated with depth. The first liquid produced deeper than 80 km is carbonatitic, changing with progressive fusion to kimberlitic and basic magmas.

Cullers et al. (1976) stated that the REE concentrations in independent carbonatite and silicate magmas produced in the manner suggested by Wyllie and Huang (1976) would be consistent with their model for carbonatite genesis. The same may be true for the primary melt model presented by Koster van Groos (1975) that was previously discussed. Assuming equilibrium, if the carbonatite and silicate magmas remain in contact with each other as they were intruded, the REE could be concentrated in the carbonatite melts relative to the silicate melts as demonstrated by Cullers et al. (1976).

Any of the processes described by Cullers et al. (1976), Wyllie and Huang (1976), or Koster van Groos (1975) could have formed the Gem Park carbonatites. However, Wyllie and Huang's model seems the most reasonable because the carbonatites could form first by partial fusion of an alkali peridotite with CO_2 at depths greater than 80 km. Progressive fusion of the source peridotite could produce the alkali basalt magma that was the presumed initial phase in Gem Park's differentiation sequence. Further fusion (4-6 per cent) could have produced the gabbroic magma.

The complementary carbonatite and alkali basalt magmas could have maintained contact with each other during intrusion. The alkali basalt differentiated to form the cumulate pyroxenites, the ijolitic melt, and nepheline syenite pegmatite. The carbonatite melt has a lower crystallization temperature ($590-600^\circ\text{C}$). It remained liquid longer than the alkali basalt melt because it was more fluid and was intruded more rapidly. Therefore, the carbonatite melt did not begin to crystallize until it

approached the surface. Thus, the carbonatite magma reached the surface last as dikes cross-cutting the other rock types. Intrusion of the carbonatite mass and its dikes was accompanied by fenitizing fluids that formed the fenite body in the center of the complex.

The cross-cutting relations between the gabbros and pyroxenites at Gem Park are not clear because either may be enclosed in the other (Parker and Sharp, 1970). This suggests that the time of intrusion of the two magmas must have been relatively close.

The Gem Park carbonatite magmas possibly formed as immiscible liquid fractions from the ijolitic magma in the manner Cullers et al. (1976) proposed for the Seabrook Lake complex. If only a small part of the ijolitic melt moved to a shallow depth, it could differentiate at a low CO_2 pressure and H_2O pressure to form the nepheline syenite pegmatite as the residual melt. The bulk of the ijolitic magma could remain at great depth and crystallize slowly until the CO_2 pressure became high enough to generate the carbonatites as an immiscible fraction.

Koster van Groos' (1975) hypothesis for the primary formation of carbonatite magmas may not be consistent with the REE concentrations. It differs from the model presented by Wyllie and Huang (1976) because it does not call for independent generation of the carbonatite and alkali basalt magmas. The heat of the primary carbonatite magma, according to Koster van Groos, partially melts the silicates to form a basaltic melt. The carbonatite then reacts with the silicate solid-liquid assemblage to form the alkaline rock series commonly associated with carbonatite complexes.

This reaction does not agree with the differentiation sequence presented in this study for Gem Park. Koster van Groos (1975) neglected trace element data; therefore, it is difficult to estimate the initial REE content of the carbonatite melt and to what extent it was affected by the reaction of the melt with the silicate solid-liquid assemblage. In view of these problems, either the model consistent with that of Wyllie and Huang (1976) or Cullers et al. (1976) seems the most reasonable.

SUMMARY

The REE distributions, Sr isotopic, and major element data are consistent with the following model for the formation of the Gem Park complex:

- 1) Partial fusion of peridotite with CO_2 at depths greater than 80 km could have formed the carbonatite magmas as suggested by Wyllie and Huang (1976). A small degree of progressive partial fusion (0.8-1.7 per cent) of the source peridotite formed a primary alkali basalt magma which differentiated to form the pyroxenites and nepheline syenite pegmatite as will be described below. Further fusion of the source peridotite (4-6 per cent) produced the gabbros.
- 2) Cumulate pyroxenite, GP-6, crystallized from the primary alkali basalt magma.
- 3) After extensive crystallization (85-90 per cent) of phases such as olivine, plagioclase, and clinopyroxene in the proportion, 5:10:85, the alkali basalt magma produced a residual liquid with a REE distribution similar to those of natural ijolites.
- 4) Cumulate pyroxenite, GP-3, equilibrated with this ijolitic melt.
- 5) The nepheline syenite pegmatite was formed as a residual liquid after extensive crystallization (80 per cent) of apatite and clinopyroxene in the proportion of 10:90 from the ijolitic melt.

- 6) If the bulk of the ijolitic intrusion remained at depth and only a small part fractionated in the above sequence near the surface, the carbonatites could have formed also as an immiscible liquid fraction from the ijolitic mass at great depth.
- 7) Gabbro, GP-1g, because of its unusual REE distribution may have formed by partial melting of a source peridotite that was depleted in the light REE, i.e., La and Ce. The degree of partial melting (4-6 per cent) and the initial REE content of the middle and heavy REE (2.3 times the chondritic values) would be the same as those used to generate the REE content of gabbro, GP-24.

APPENDICES

Appendix A - Major Element Techniques

Preparation of Samples

Each sample was ground to less than 100 mesh and 0.10 g of this sample was placed in a Teflon-lined bomb along with 1 ml aqua regia, and 6 ml HF. The bomb was tightly sealed, and was heated at 110°C in a drying oven for approximately 45 minutes. After cooling the sample to room temperature, the sample solution was transferred by washing with water into a Teflon beaker containing 4 g of H_3BO_3 . The H_3BO_3 was dissolved in a volume of about 75 ml of solution by using a Teflon stirring rod. The solution was then transferred to a 100 ml volumetric flask, 1 ml of La stock solution/100 ml was added and the volume was brought to 100 ml. The resultant solution contained 6 ml HF acid, 4 g H_3BO_3 , 1 ml aqua regia, and 1 ml La stock solution/100 ml.

Preparation of Standard Solutions

Standard solutions were prepared from Fisher Scientific stock solutions of 1000 $\mu\text{g}/\text{ml}$ for Al, Si, Ca, Fe, K, Mg, Na. Stock solutions for Ni (10 $\mu\text{g}/\text{ml}$), Co (10 $\mu\text{g}/\text{ml}$) and Cr (20 $\mu\text{g}/\text{ml}$) were prepared by Dr. Chaudhuri from the original Fisher stock solutions. He also made the Ti stock solution by weighing 0.2 g of spec pure Ti metal into a Teflon beaker along with 20 ml of 6N vycor-distilled HCl and 1 ml of HF. The solution was warmed for 5-10 minutes until the metal dissolved. Then the solution was transferred into a 1000 ml volumetric flask with demineralized water (concentration = 200 $\mu\text{g}/\text{ml}$).

The Ba stock solution was prepared by weighing out 0.12 g of $\text{BaCl}_2 \cdot 2\text{H}_2\text{O}$ into a Teflon beaker. It was dissolved in 10 ml of demineralized water and 1 ml of 2N HNO_3 . The volume was brought to 1000 ml in a volumetric flask, and the resulting concentration of the solution was 70 $\mu\text{g}/\text{ml}$ of Ba. The La stock solution was prepared so as to produce a concentration of 4986 $\mu\text{g}/\text{ml}$ La.

The standard solutions were prepared by taking appropriate quantities of stock solutions and adding to each stock solution a mixture of 4 g of boric acid, 1 ml of aqua regia, 6 ml of HF, and 1 ml of La stock solution for each 100 ml of solution.

Table A₁ lists the concentrations of the elements in the Standards A₁, A₂, and the Na standards which I prepared. Dr. Chaudhuri prepared his own Si stock solution and I used the Fisher Scientific Si stock solution. Thus, our Si concentrations differ. In Standard A₁, I used the undiluted stock solutions (1000 $\mu\text{g}/\text{ml}$) for Co, Ni, and Cr. This error resulted in the extremely high concentrations of these trace elements. Table A₂ lists Dr. Chaudhuri's standard concentrations.

The Na standards were made by taking 4 ml and 2 ml of Na stock solution (1000 $\mu\text{g}/\text{ml}$), 10 ml of blank solution and diluting each standard to 100 ml. The two Na standards contained 40 $\mu\text{g}/\text{ml}$ and 20 $\mu\text{g}/\text{ml}$ respectively.

The blank solution contained 6 ml of HF, 4 g of boric acid, 1 ml of LaCl_3 , and 1 ml of aqua regia. This mixture was diluted to 100 ml in a volumetric flask.

Table A₁. Standard Solution Concentrations* ($\mu\text{g/ml}$)

Elements	Standard A ₁	Standard A ₂	Na Std. 40	Na Std. 20
Si	100	100		
Al	100	100		
Fe	100	100		
Ca	100	100		
K	50	50		
Na	50	50	40	20
Mg	50	50		
Co	20	0.2		
Ba	0.7	0.7		
Ni	30	0.3		
Cr	20	0.4		
Ti	---	20		

* All solutions prepared by Roden (6/75).

Table A₂. Element Concentrations in Dr. Chaudhuri's Standard Solutions ($\mu\text{g/ml}$)

Element	Standard A	Standard B	Standard C	Standard D
Si	348	174	69.6	1.39
Al	100	50	20	0.4
Fe	100	50	20	0.4
Ca	100	50	20	0.4
K	50	25	10	0.2
Na	50	25	10	0.2
Mg	50	25	10	0.2
Ti	20	10	4	0.08
Co	0.2	0.1	0.05	---
Ni	0.3	0.15	0.1	---
Ba	0.7	0.35	0.14	---
Cr	0.4	0.2	0.1	---

A solution of RbCl (greater than 1000 $\mu\text{g/ml}$) was added to the samples and standards for the analyses of Na and K in a ratio of 5 parts sample (standard) to 1 part of Rb. This counteracted the tendency of these elements to ionize. La has a similar effect on Ca and Mg. It was added to the samples and standards during dissolution.

Optimum Settings

Table A₃ shows the optimum instrumental settings for each element determined on a Perkin-Elmer 305B atomic absorption spectrophotometer. When the samples and standards were used in undiluted concentrations, the results were less accurate than when the concentrations were diluted in half with demineralized water. The strong concentrations of HF, aqua regia and boric acid formed deposits on the burner and corroded the nebulizer which added to the analytical error.

Results

Table A₄ compares my analyses with the accepted values cited in the literature (Flanagan, 1969). The best results were obtained for K, Mg, and Al; Ca, Na, Ti, and Fe were not as accurate. The percentage of error from the accepted value is also given.

Other Analytical Procedures

The CO₂ content of the carbonatites was determined by loss on ignition. The samples were dried at 110°C for one hour. They were then weighed accurately into portions of about 0.5 g, into covered platinum crucibles that had been previously ignited and weighed. They

Table A₃. Optimum Instrumental Settings for Model 305B
Perkin-Elmer Atomic Absorption Spectrophotometer

Elements	Al	Ca	Fe	K	Mg	Na	Ti
Emission (E) OR Absorption (A)	A	A	A	E	A	E	A
Fuel Type:							
Nitrous Oxide (N)	N	A-A	A-A	A-A	A-A	A-A	N
Acetylene-air (A-A)							
Air Flow*		6.5	6.5	6.0	6.0	6.0	
Fuel Flow*		5.0	5.0	5.0	5.0	5.0	
Burner Position:							
Parallel to light //	//	⊥	//	⊥	⊥	⊥	//
Perpendicular to light ⊥							
Sample Concentration:							
Undiluted (U)	D/2	U	D/2	D/2	D/2	D/2	U
Diluted in half (D/2)							

* Units given in the Perkin-Elmer manual.

Table A₄. Comparison of Standard Rock Values in Weight Per Cent and Error

Elements	Roden	BCR-1 Flanagan (1969)	Per Cent Error	Roden	AGV-1 Flanagan (1969)	Per Cent Error
K ₂ O	1.67	1.68	0.6	3.01	2.89	4.2
Na ₂ O	3.50*	3.31	5.7	4.42	4.33	2.1
CaO	6.62	6.95	4.7	3.64	4.98	26.9
MgO	3.37	3.28	2.7	1.49**	1.49	0.3
(Total Fe as Fe ₂ O ₃)	13.36(A ₁)* 14.94(A ₂)*	13.50	1.0 10.7	7.26	6.9	5.2
Al ₂ O ₃	---	---	---	18.79	17.01	10.5
TiO ₂	2.31	2.23	3.6	---	---	---

* Undiluted run.

** Weight per cent has been rounded.

were ignited at 1000°C for one hour, cooled and weighed. The accuracy of these determinations was tested by analyzing standard carbonate, 400, a dolomite. According to Ingamells and Suhr (1967), there was only 1.4 per cent error between the value I obtained (46.67 per cent CO₂) and the accepted one (47.36 per cent CO₂).

MnO and Na₂O were determined by instrumental neutron activation analysis by Dr. Robert L. Cullers and Rich Koch of Kansas State University, Manhattan, Kansas. The peak areas were calculated in the same manner as described for the REE peaks. The weight per cent of MnO and Na₂O in the sample were calculated by the following formula:

$$\frac{\text{wt. per cent Standard I}}{\text{wt. per cent sample}} \times \frac{\text{cpm sample}}{\text{cpm Standard I}} \times \frac{\text{wt. per cent MnO Std. I}}{1} = \frac{\text{wt. per cent}}{\text{sample}}$$

The Na₂O values determined by INAA are identical to those determined by atomic absorption.

Appendix B - Radiochemical Neutron Activation Analysis

Preparation of Samples

The samples were ground in a steel mortar and pestle to a size less than 100 mesh. About 0.3 g (± 0.0002 g) for the alkaline rock samples and 0.2 g (± 0.0002 g) for the carbonatite samples and liquid irradiation standard were heat sealed in polyethylene irradiation vials. Iron wire flux monitors were wrapped spirally around that portion of the capsule that contained the sample. The samples were placed in the core of the Kansas State Triga Mark II reactor at an estimated flux of 10^{13} neutrons/cm²/sec for one to two hours. Four samples and two standards were irradiated in each batch.

Chemical Separation of the REE Group

The following procedure was developed by Denechaud et al. (1970). A crucible containing a REE carrier solution was prepared for each of the irradiated samples. About 50 mg of reagent grade NaCl, 2.00 ml of the REE carrier solution, and 1.00 ml of a solution containing Y⁸⁸ tracer was placed in a clean, 40 ml zirconium crucible. The Y⁸⁸ was made commercially (Nuclear Science and Engineering Corp.) and was used in the determination of the chemical yield. After the NaCl was dissolved, the solution was evaporated to dryness in the crucible under a heating lamp, then warmed to about 150°C in an oven to insure removal of most of the water. The NaCl aids the mechanical mixing of the irradiated sample and carrier prior to fusion. The same quantities

of carrier and Y^{88} tracer as used for each sample were pipetted into a 50 ml Erlenmeyer flask to receive the irradiation standard.

Each irradiated sample was carefully poured into its zirconium crucible, covered with about 12 g of Na_2O_2 , and mixed with the carrier and Na_2O_2 by stirring with a nickel steel spatula. The mixture was then fused at red heat over a Meeker burner and kept completely molten for about 45 seconds.

Each crucible was allowed to cool in air nearly to room temperature, then was placed on its side in a 400 ml beaker containing about 80 ml of distilled water to digest the fusion cake. The spatula was also placed in the beaker so that any of the material adhering to it will be mixed with the rest.

When the fusion cake was digested completely, the surface of the watch glass was rinsed with a stream of concentrated HCl into a beaker. Additional HCl was added to the beaker, while stirring, until the precipitate was dissolved.

About 25 g of solid NH_4Cl were dissolved in the solution. Concentrated aqueous ammonia was added to a pH of 9 or greater to precipitate the REE, Fe, and Al, as hydroxides. The precipitate was centrifuged and the supernate discarded into the radioactive waste. This process was repeated after the beaker had been rinsed with distilled water and the washings added to the centrifuge tube.

The next step was the first in the removal of silica. The hydroxide precipitate was dissolved in concentrated HCl. The volume was

estimated and concentrated HCl was added to increase the volume by 25 per cent. The solution was transferred to a beaker and boiled over a hot plate for 10 minutes. It was then cooled in an ice bath to 60°C. An additional 3 ml of concentrated HCl and 1.5 ml of a freshly prepared 1.5 per cent gelatin solution were added, dropwise, with constant stirring. The silica precipitated was centrifuged out and the supernate was poured into a 250 ml separatory funnel. The silica was rinsed with 15 ml of 8M HCl, centrifuged out, and the rinse was added to the separatory funnel. The rinsing step was repeated until the silica residue was colorless, or a maximum of four times, whichever came first. Removal of silica facilitates the extraction of Fe, which improves the chemical yields of the REE.

About 100 ml of isopropyl ether were added to the separatory funnel, then equilibrated with the HCl solution by shaking. The aqueous layer was drained into a 400 ml beaker. The ether phase, which contains most of the Fe, was discarded into a special radioactive waste beaker containing a few grams of Na_2SO_3 (to inhibit the formation of peroxides) and allowed to evaporate. The extraction was repeated with 50 ml of isopropyl ether to remove the last traces of Fe.

The HCl solution in the 400 ml beaker was warmed on a hot plate to remove traces of ether. The solution was then cooled to about 60°C in an ice bath and made basic to pH 10-12 by the slow addition, with constant stirring, of 16M NaOH. The REE were quantitatively precipitated as hydroxides while Al remained in solution. The precipitate was centrifuged out and the supernate discarded.

The hydroxide precipitate was rinsed with 15 ml of distilled water, centrifuged, and the rinse discarded. This step was repeated. The hydroxides were then dissolved in the minimum quantity of 6M HCl required. To minimize selective loss of the lightest and heaviest REE, the resulting solution should have as small a volume as possible, be free of Na^+ , NH_4^+ , and Fe^{3+} , and not be excessively acidic. The solution was heated nearly to boiling in a water bath, then 1.3 ml of saturated oxalic acid solution was added with intensive stirring. If large amounts of Zr are present (as a result of excessive attack of the crucible during fusion), the hydroxide precipitate will have a dark blue-green color. In this case, the amount of oxalic acid added must be doubled or tripled to keep the Zr in solution.

The REE oxalates will form a cloudy, white precipitate on addition of the oxalic acid. The oxalate precipitate should become more coarsely crystalline within a few minutes. The centrifuge cone containing the solution was then removed from the water bath and allowed to cool and digest for about an hour at room temperature.

The REE oxalates were filtered under suction through a chimney with an inside diameter of 1.5 cm onto a circle of Whatman No. 50 paper. The sides of the chimney were rinsed with ethanol, then diethyl ether, to dry the precipitate. After the chimney was removed, the sample was mounted for radioassay by being centered exactly on a counting card, covered with a thin plastic film, and fastened into place with transparent, gummed tape.

The last step in this process was to ready the irradiation

standard for radioassay. It was opened and rinsed with distilled water into the Erlenmeyer flask containing its carrier and Y^{88} chemical yield tracer. The volume at this point was about 15 ml. The solution was warmed nearly to boiling on a hot plate and 1.3 ml of saturated oxalic acid were stirred in. The REE oxalates were left to digest on the hot plate for a few minutes, then set aside to cool for 1 hour at room temperature. They were mounted for radioassay in the same manner as were the samples.

Gamma Ray Spectrometry

A 25 cm³ Ge(Li) detector with either a Northern Scientific or a Technical Measurement Corporation 4096 channel analyzer and associated electronics were used for all samples. A resolution of 4.0 keV for the 1331 keV peak of Co^{60} can be obtained by using these systems. Cullers et al. (1974) summarized the results they obtained for the USGS standard rock BCR-1 using this technique. Their results agree well with those of Denechaud et al. (1970).

Because of the variety of half-lives among the REE, four count sets are necessary to obtain the REE most important in REE distributions. Denechaud et al. (1970) gave a detailed description of the REE isotope and gamma lines. The first count set was done on the same day as the chemical separation. The samples were counted for approximately 20 minutes each. Sm^{153} and Eu^{152} are the most important nuclides counted in this count set.

The second count set was made 3 days after the end of irradiation.

In this set, the samples were counted for one hour and La^{140} , Sm^{153} , and Ho^{166} were obtained. The third count set was done at 10 days after the end of irradiation. In this set, the counting period was extended to approximately 6 hours and La^{140} , Lu^{177} , Tb^{160} , and Yb^{175} were obtained. The fourth count set was done at 40 days after the end of irradiation. This was another 6 hour count set and Ce^{141} , Eu^{152} , Gd^{153} , Tb^{160} , and Yb^{175} were obtained. The geometry of the samples and standard was kept constant for each count set and below 8 per cent dead time.

Peak Integration

Before peak areas were calculated, each peak was graphed with the background extended at least 10-20 channels on either side of the center channel. A smooth curve was drawn through the background and the baseline was drawn through this curve. If the peaks did not show any drift, then the sum of 7 channels was used to calculate the peak area. If drift did appear, then the sum of 11 or more channels was used, i.e., the whole peak was summed.

After the baseline was drawn, the center channel was marked on it. The counts per channel obtained for the center channel on the baseline was considered the average background. This was then multiplied by the number of channels summed to produce the base correction. The sum peak minus the base correction gives the net peak.

The net peak is the total area of the peak. The total area was divided by the number of minutes it was counted to get the

counts per minute. This was done for the standard first and then for all the REE obtained in that count set. Next, the median time for the standard and all the samples was determined. The difference between the standard and each sample was calculated. This was used to determine the decay factor for each REE in each sample.

The decay factor was calculated by the formula, $e^{\lambda t}$, where t = the difference between the standard and sample median times and $\lambda = \frac{0.693}{t_{1/2}}$. The counts per minute for each REE was multiplied by the decay factor to get the corrected peak. This was then divided by the counts per minute of the standard to produce the ratio to the standard for each REE.

Determination of the Chemical Yields

In the 3-day, 10-day, and 40-day count sets, the area for the 1.836 MeV peak of Y^{88} was calculated for the standard and each sample. The ratios of the sample to the standard for each count set were averaged and used in the determination of the chemical yields.

Because complete recovery of the carrier originally added to the samples was not possible and losses for the individual REE were not uniform, it was necessary to determine the percentage recovered for every REE. The chemical yield for each REE was determined by reirradiation of a part of the recovered carriers of the samples and standard after the 40-day count set.

The following procedure is taken from Denechaud et al. (1970). The mounted sample of REE oxalate was cut open and about 1/8 of the precipitate was removed with a spatula and spread evenly onto a

3/4 cm diameter circle of Whatman No. 50 filter paper. Two drops of a 2 per cent solution of polystyrene in ethyl acetate were placed on the precipitate, then the solvent was evaporated away under a heating lamp. A thin coating of lacquer (Krylon No.1302 coating) was sprayed on to hold the precipitate in place. The filter circle and precipitate were heat-sealed between two sheets of polyethylene film. The packets prepared from the samples and the standard were bound tightly together with tape and irradiated for two hours at a neutron flux of $5.10^{12} \text{ n.cm}^{-2} \text{ sec}^{-1}$.

The irradiated carriers were left to decay in the reactor pool for several days. On the eighth day after irradiation, each was mounted on a card and counted for about 50 minutes on one of the Ge(Li) detectors. Relative chemical yields were obtained for La, Sm, Eu, Tb, Yb, and Lu by comparing peak ratios for the REE in the samples to those of the standard. The relative yields for Ce, Gd, Dy, and Ho were obtained from a graph of relative yield vs. REE atomic number by interpolation.

The relative yield for Dy was converted into an absolute chemical yield for that element by multiplying it by the average ratio of the Y^{88} tracer activity of the sample to that of the standard which was already calculated. An absolute chemical yield for each of the other REE was then obtained by multiplying the ratio of the relative chemical yield for the element to that for Dy by the absolute chemical yield for Dy.

The last correction factor in the REE analysis was for the flux of the reactor. This was done by calculating the specific activity of the Fe wires which were wrapped around the standard and samples when they were first irradiated. The Fe wires were mounted on a counting card and counted after the 40-day count set. The peak areas were calculated in the same way as they were for the REE. Once the counts per minute have been determined, the specific activity (counts/min/mg) was calculated and the ratio of the standard Fe specific activity to the sample Fe specific activity was also calculated.

REE Concentrations

The final ppm of each REE for each sample was determined by averaging the sample/standard ratios for that REE in all count sets. This ratio was then multiplied by the chemical yield determined for that REE, the ratio of standard/sample Fe specific activity, and the ratio of the standard weight/sample weight. The result was the final ppm for that REE for that sample.

Two runs of four samples each were made for the Gem Park rocks. Run GP-1 included GP-1g, gabbro, GP-3, pyroxenite, GP-4, nepheline syenite pegmatite, and GP-6b, carbonatite. In this run, it was impossible to do the 1-day count set and the 10-day count set could not be used because the peaks showed considerable drift. The chemical yield for just the 3 and 40-day count sets was excellent for all samples. It ranged from 93 per cent for the carbonatite to 99 per cent for the gabbro.

Run GP-2 included GP-6, pyroxenite, GP-7b, carbonatite, GP-9a&b, carbonatite, and GP-8, carbonatite. All the count sets were used for this run. However, the results were not as good as for the first run. The chemical yield ranges from 43 per cent for GP-8 to 83 per cent for GP-9a&b.

Gabbro, GP-24, was analyzed by Dr. Robert L. Cullers at Kansas State University by the same processes as listed above.

Appendix C - Rb-Sr Analytical Techniques

Dissolution of Samples

After the Rb and Sr contents had been estimated by x-ray spectrography, the sample weights for dissolution could be calculated to yield a minimum of 15 micrograms of rubidium or strontium in solution. This procedure gave sufficient rubidium or strontium salt for repeat analyses if a recovery of at least 50 per cent was assumed. The dissolution procedures are those of Chaudhuri (1966), Chaudhuri and Brookins (1969), and Methot (1973).

The Gem Park samples were non-refractory so they were dissolved in clean 100 ml Teflon dishes. For unspiked runs, the samples were roughly weighed and wetted with a few ml of water before the acids were added. This helped to prevent scattering and loss of the sample on addition of the acids. In the spiked runs, a few ml of water were added to the dish first and then the weighed sample and spike solution were added.

A mixture of approximately 20 ml of hydrofluoric acid and 2 ml perchloric acid per gram of sample was added to the wetted samples to digest them. The dishes were heated on a hot plate for several hours to drive off the HF, first, and then the perchloric acid. This evaporated the solutions to a perchlorate mush. The perchlorate residues for rubidium analysis were cooled and stored for separation. Those residues for strontium analysis were redissolved in approximately 20 ml of 1N hydrochloric acid and evaporated to about 15 ml. After

several hours of cooling, the residues were removed from the HCl solutions by filtration.

Ion-Exchange Separations

Cation-exchange techniques were used to recover strontium and rubidium from sample solutions. In the strontium columns, a cross-linked resin in bead form (Dowex 50W-X8) was used. The rubidium separations were done in columns of granular zirconium phosphate.

Strontium--About 300 ml of 6N hydrochloric acid was used first to clean the ion exchange columns used for strontium separations. This washing was followed by a second wash with 600 to 700 ml of 2N hydrochloric acid. Afterwards, the surface of the beds were leveled.

Several drops of Sr^{85} tracer solution were added to each sample solution to track the position of strontium in the column. The solutions were poured carefully into the columns and allowed to settle into the resin beds.

Each of the columns was washed with 2N hydrochloric acid. The radioactive portion of the acid volume was collected in four 10 to 20 ml aliquants. The aliquants were evaporated to volumes of a few ml. The acid volumes with the highest activity were transferred to a single beaker. After they had been evaporated to dryness, the residues were redissolved in 3 to 4 ml of 3N nitric acid. The solutions were evaporated to about 1 ml and transferred to 2 ml Vycor glass beakers for final evaporation to dryness. The nitrates were heated over a burner to oxidize organic residues and stored for analysis.

Rubidium--The mushy perchlorate residues were washed in a few ml of methanol until all yellow color had disappeared. The precipitate that was left was collected and transferred to centrifuge tubes. The methanol containing the residues was stirred, centrifuged, and the supernate discarded.

After several methanol washings, the precipitate from the centrifuge tubes was transferred to a clean crucible by rinsing with several drops of water. The solutions were evaporated to dryness. Making a solution of the dry material in a 3 to 5 ml of 0.5N nitric acid was the final step before the solutions went into the Rb columns.

300 to 400 ml of 6N nitric acid were used first to clean the exchange columns of granular zirconium phosphate. This was followed by a wash with about 100 ml of 0.5N nitric acid. Between the addition of sample solutions, the columns were cleaned with 200 ml of 6N nitric acid followed by 100 ml of 0.5 nitric acid.

After the solutions had passed through the columns, potassium and sodium were removed by washing each column with 100 ml of 0.5N nitric acid. Further washing with 40 ml of 6N nitric acid brought out rubidium. The acid solutions were collected in single beakers and evaporated to about 1 ml. This was transferred to 2 ml Vycor glass beakers for evaporation to dryness and storage for analysis.

Appendix D - Thin-Section Descriptions

Alkaline Rocks

GP-4-Nepheline Syenite Pegmatite--holocrystalline, coarse-grained, hypidiomorphic-granular, nepheline syenite pegmatite. It contains 60.1 per cent subhedral to euhedral prismatic perthite grains (4-6 mm wide) meshed together. They are heavily altered to illite, which is crystallographically controlled, and they contain water-filled vacuoles, which cause the perthite to have a brownish, turbid appearance.

Nepheline is also a major component (35.4 per cent). It occurs as interstitial, anhedral grains varying in size from 0.72 mm to 6.0 mm in width. The grains have a turbid appearance due to the presence of water-filled vacuoles.

Aegirine-augite (1.9 per cent) is present in euhedral to subhedral cross sections (0.54 mm to 1.80 mm in diameter) and subhedral to anhedral prismatic grains (2.5 mm in diameter). It is dark green in thin section and strongly pleochroic (z = yellow, y = yellowish green, x = dark green). Some crystals show zoning from bright green in the center to deep green on the edges in the x direction and from yellow-brown on the edge to yellow in the center in the z direction. They give an extinction angle ($c\wedge x$) of -31° .

Minor amounts of iron ore (1.5 per cent) in anhedral grains (1.44 mm in diameter), sphene (0.8 per cent) in euhedral crystals (1.52 mm in diameter), and natrolite (0.4 per cent) in fibrous aggregates (1 mm in diameter) that rim grains of iron ore, are also present.

GP-1g-Gabbro--holocrystalline, medium-grained, xenomorphic-granular gabbro. It contains 43.5 per cent colorless, anhedral, augite prismatic grains (2.2 mm in diameter) and anhedral to subhedral cross sections (0.9 mm in diameter). Some sections show schiller structure produced by small mineral inclusions, mainly iron ore, oriented parallel to crystallographic directions. The augite grains show an extinction angle ($z\wedge c$) of 45° . They show the beginnings of replacement by kaersutite and iron ore.

Plagioclase (39.6 per cent) occurs as anhedral laths varying in size from 0.6 mm to 2.4 mm in length. In composition, the plagioclase is labradorite (An_{54-62}). It does show alteration to water-filled vacuoles. Texturally, the plagioclase grains are arranged in a jackstraw pattern generally surrounded by clinopyroxene.

Ti-rich kaersutite is present (6.6 per cent). It is strongly pleochroic (z = dark red-brown, y = reddish-brown, x = light yellow-brown) and has an extinction angle ($z\wedge c$) of 2° . It occurs as anhedral grains (0.36 mm to 0.90 mm in length) which have altered rims of green pleochroic (z = dark green, y = medium green, x = light green) amphibole, probably Na-rich kaersutite.

Anhedral grains of iron ore (10.2 per cent) averaging 1.08 mm in diameter are also present. They tend to replace the augite and kaersutite grains. A trace of apatite (less than 1 per cent) can be found.

GP-2b-Lamprophyre--holocrystalline, porphyritic, subophitic, pandiomorphic-granular, lamprophyre. It contains about 60 per cent plagioclase (An_{28} -Oligoclase) as euhedral phenocrysts (0.90 mm in length) and as subhedral to anhedral laths in the groundmass (0.72 mm in length). The plagioclase shows both Carlsbad and Albite twinning and alteration to water-filled vacuoles.

Kaersutite (about 38 per cent) is present in euhedral phenocrysts (1.08 mm in length) and in subhedral to anhedral laths in the groundmass (0.54 mm in length). It has the same optical properties as described under gabbro, GP-1g. Anhedral green amphibole grains (0.18 mm in length) occur as alteration products of the kaersutite. These also have the same optical properties as described under GP-1g. Minor iron ore (about 2 per cent) is present as anhedral grains (0.36 mm in diameter).

GP-3-Pyroxenite--holocrystalline, coarse-grained, hypidiomorphic-granular, pyroxenite. Augite is the major component (73.2 per cent). It occurs as euhedral cross-sections (0.5 mm in diameter) and as subhedral to anhedral grains (2.16 mm in diameter). Opaque minerals, probably iron ore, are oriented along crystallographic directions producing the schiller structure. It shows strong oscillatory and concentric zoning and an extinction angle ($z\wedge c$) of 56° . It is colorless in thin section and shows no pleochroism. The alteration products for augite include chlorite, sphene and magnetite (iron ore). Kaersutite (19.6 per cent) occurs as a reaction product of the melt with the pyroxene grains. Anhedral grains of kaersutite (0.36 mm in diameter), which comprise about 2 per cent of the total kaersutite, appear to be cumulus. The

kaersutite grains have the same optical properties as described under gabbro, GP-1g. The kaersutite grains are altered to the green pleochroic amphibole that was present in gabbro, GP-1g, and lamprophyre, GP-2b.

Sphene (4.4 per cent) is present as anhedral and fibrous-radial aggregates (0.55 mm in diameter). Plagioclase (0.8 per cent) can be found as interstitial, anhedral grains (0.2 mm in diameter). It was impossible to measure the An content because of the size of the grains and the scarcity of sections showing albite twinning.

This pyroxenite is texturally a cumulate because it contains a mesh of randomly-oriented euhedral, subhedral and anhedral pyroxene grains with interstitial plagioclase trapped in between them.

GP-5-Pyroxenite--holocrystalline, coarse-grained, xenomorphic-granular, pyroxenite. It contains 76.5 per cent subhedral to anhedral augite grains (1.62 mm in width) and 16.4 per cent anhedral kaersutite grains (0.68 mm in width), which replace the augite. The pleochroic green amphibole grains (0.72 mm in width) which form as an alteration product of the kaersutite grains are also present. All of these minerals have the same optical properties as those given under GP-1g, gabbro.

Plagioclase (3.1 per cent) occurs as interstitial grains (0.68 mm in width) with labradorite composition (An_{54}). This plagioclase is fairly fresh. It contains some water-filled vacuoles and minor amounts of illite.

Anhedral grains of iron ore (0.5 mm in diameter) are present

(2.9 per cent). About 0.7 per cent of a sulfide, probably pyrite, which is mostly altered to limonite, occurs as anhedral granular aggregates 1.5 mm in width. There is also a trace of granular sphene.

This pyroxenite also shows cumulate textures in its mesh of randomly-oriented augite grains as does pyroxenite, GP-3.

GP-6-Pyroxenite--holocrystalline, medium-grained, xenomorphic-granular, pyroxenite. It contains 38.4 per cent augite as subhedral to anhedral grains (0.72 mm in diameter). These show an extinction angle ($z\wedge c$) of 49° and concentric zoning. They are colorless in thin section and contain opaque mineral inclusions that produce the schiller structure. Kaersutite and iron ore are the alteration products of the augite grains.

Plagioclase (An_{59} -Labradorite) is present in a much greater percentage than in the other pyroxenites (23.3 per cent). It occurs mainly as interstitial anhedral grains (0.36 mm in diameter) but it also is present as larger subhedral to anhedral laths (1.08 mm in diameter). The plagioclase is highly altered to illite.

This pyroxenite contains kaersutite (21.9 per cent) as do the others. It occurs as anhedral grains (1.62 mm in diameter) which have reaction rims of anhedral green amphibole grains (0.72 mm in width). About 2 per cent of the kaersutite appears to be cumulus as in GP-3, pyroxenite. Both of these minerals have the same optical properties as were described under GP-1g, gabbro. Kaersutite also shows alteration to granular sphene.

This pyroxenite also shows cumulate textures in its clumps of

randomly-oriented pyroxene grains. The plagioclase is mostly interstitial and the larger grains are segregated together by the surrounding cumulate pyroxene grains.

Carbonatites

GP-1a-Carbonatite--holocrystalline, coarse-grained, xenomorphic-granular, rauhaugite. It contains 98 per cent dolomite which occurs as anhedral grains (0.82 mm in diameter). Iron ore is present in minor amounts (1 per cent) as anhedral grains (0.2 mm in diameter). Phlogopite (0.7 per cent) is also present as elongate, bladed, anhedral grains (0.28 mm in length). They are yellow in thin section and are pleochroic (z = yellow-green, y = yellow-green, x = yellow).

Pyrochlore is present in minor amounts (0.2 per cent) as anhedral granular aggregates (0.3 mm in diameter). Optically, it is isotropic and brown-black in color. A trace of apatite (0.1 per cent) can also be found as anhedral grains (0.3 mm in diameter).

This rauhaugite is an example of what Parker and Sharp (1970) considered a dolomite-pyrochlore carbonatite.

GP-6b-Carbonatite--holocrystalline, coarse-grained, xenomorphic-granular, aplitic, rauhaugite. It contains 87.9 per cent equigranular, anhedral, dolomite grains (1.26 mm in width). Apatite occurs as lens-like masses of elongate subhedral to anhedral grains (0.54 mm in width). They compose 4.7 per cent of the rock.

Anhedral grains of iron ore (0.9 mm in width) are also a minor constituent (4.2 per cent). Pyrochlore is present (1.8 per cent) as

anhedral grains (2.16 mm in diameter) and as minute granular masses concentrated with the apatite masses and along fractures in the rock.

A fibrous blue amphibole (probably crocidolite) occurs as an accessory mineral (1.9 per cent). It forms fibrous aggregates and anhedral elongate grains (0.11 mm in width) which are concentrated along apatite-pyrochlore lenses.

This rauhaugite is a dolomite-apatite-pyrochlore-blue amphibole carbonatite.

GP-7b-Carbonatite--holocrystalline, fine-grained, xenomorphic-granular, rauhaugite. It contains 66.5 per cent dolomite in anhedral grains (0.22 mm in diameter). Secondary vein quartz (32.7 per cent) is present in the cavities. It occurs as anhedral grains (0.90 mm in diameter) which show straight to slightly undulose extinction and abundant water-filled vacuoles.

Accessory minerals include pyrochlore (0.7 per cent), which forms anhedral granular aggregates (0.90 mm in diameter), and a trace of apatite.

This rauhaugite is a dolomite-pyrochlore carbonatite.

GP-8-Carbonatite--holocrystalline, medium-grained, xenomorphic-granular, aplitic, rauhaugite. It contains 99.5 per cent dolomite as interlocking anhedral grains (0.18 mm to 0.73 mm in diameter). They contain minor inclusions of iron ore. Apatite is the only minor constituent (0.5 per cent). It occurs as anhedral elongate grains and aggregates which vary from 0.1 - 0.2 mm in length .

This is a dolomite-apatite rauhaugite.

GP-9a&b-Carbonatite--holocrystalline, fine-grained, xenomorphic-granular, rauhaugite. It contains 98 per cent dolomite as anhedral grains (1.08 mm in diameter). Pyrochlore occurs as anhedral granular aggregates (0.2 mm in diameter) and fibrous blue amphibole (crocidolite) is also present as anhedral elongate grains (0.1 mm in length) which are concentrated in the fracture fillings. Both of these minerals have estimated concentrations of about 1 per cent. This slide could not be included in the modal analysis.

This rauhaugite is a dolomite-blue amphibole-pyrochlore carbonatite.

Table D₁. Modal Analyses of the Alkaline Rocks
Per Cent by Volume (1300 Points)

	GP-1g Gabbro	GP-3 Pyroxenite	GP-4 Nepheline Syenite Pegmatite	GP-5 Pyroxenite	GP-6 Pyroxenite
Augite	43.5	73.2	---	76.5	38.4
Perthite	---	---	60.1	---	---
Nepheline	---	---	35.4	---	---
Plagioclase	39.6	0.8	---	3.1	23.3
Kaersutite	6.6	19.6	---	16.4	21.9
Iron Ore	10.2	2.1	1.5	2.9	16.1
Aegirine-augite	---	---	1.9	---	---
Sphene	---	4.4	0.8	trace	0.3
Apatite	trace	---	---	---	---
Pyrite	---	---	---	0.7	---
Natrolite	---	---	0.4	---	---

Table D₂. Modal Analysis of the Carbonatites
Per Cent by Volume (1300 Points)

	GP-1a	GP-6b	GP-7b	GP-8
Dolomite	98.0	87.9	66.5	99.5
Apatite	trace	4.7	---	0.5
Iron Ore	1.0	4.2	---	---
Pyrochlore	0.2	1.8	0.7	---
Fibrous Blue Amphibole	---	1.9	---	---
Sphene	---	---	0.1	---
Phlogopite	0.7	---	---	---
Quartz (secondary)	---	---	32.7	---

REFERENCES

- Abbey, S.: Analysis of rocks and minerals by atomic absorption spectroscopy, Part 2. Determination of total Fe, Mg, Ca, Na, and K. Geol. Surv. of Canada, 68-20, 21 (1968).
- Bailey, D. K., Schrairer, J. F.: The system $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{Fe}_2\text{O}_3-\text{SiO}_2$ at 1 atmosphere and the petrogenesis of alkaline rocks. Jour. Pet. 7, 114-170 (1966).
- Bell, K., Powell, J. L.: Strontium isotopic studies of alkalic rocks: the alkalic complexes of eastern Uganda. Bull. Geol. Soc. Amer. 81, 3481-3490 (1970).
- Buckley, D. E., Cranston, R. E.: Atomic absorption analyses of 18 elements from a single decomposition of aluminosilicate. Chem. Geol. 7, 273-284 (1971).
- Chaudhuri, S.: The geochronology of the Keeweenawan rocks of Michigan and the origin of the copper deposits. Ph. D. Thesis, Ohio State University, 200 p. (1966).
- Chaudhuri, S., Brookins, D. G.: The isotopic age of the Flathead Sandstone, Montana. Jour. Sed. Pet. 39, 364-368 (1969).
- Christman, R. A., Brock, M. R., Pearson, R. C., Singewald, Q. D.: Geology and thorium deposits of the Wet Mountains, Colorado—a progress report. U. S. Geol. Survey Bull. 1072-H, 491-535 (1959).
- Cullers, R. L., Medaris, L. G., Haskin, L. A.: Gadolinium: distribution between aqueous and silicate phases. Science 169, 580-3 (1970).
- Cullers, R. L., Medaris, L. G., Haskin, L. A.: Experimental studies of the distribution of rare earths as trace elements among silicate minerals and liquids and water. Geochim. Cosmochim. Acta 37, 1499-1512 (1973).
- Cullers, R. L., Yeh, L. T., Chaudhuri, S., Guidotti, C. V.: Rare-earth elements in Silurian pelitic schists from N. W. Maine. Geochim. Cosmochim. Acta 38, 389-400 (1974).
- Cullers, R. L., Medaris, L. G., Chaudhuri, S.: Rare-earth elements in carbonatite and cogenetic alkaline rocks: examples from Seabrook Lake and Callander Bay, Ontario. Submitted, Contrib. Min. Petrol. (1976).

- Daly, R. A.: Igneous rocks and depths of the earth. New York: McGraw-Hill Book Company, 598 pp. (1933).
- Dawson, J. B.: Reactivity of the cations in the carbonatite magma. Geol. Assoc, Canada Proc, 15, 103-113 (1964).
- _____. The kimberlite-carbonatite relationship. Mineralog. Soc. India I. M. A. volume, 1-4 (1966).
- _____. Geochemistry and origin of kimberlite. In: Ultramafic and Related Rocks, Wyllie, P. J., Ed., New York: John Wiley and Sons, 264-278 (1967).
- Denechaud, E. B., Helmke, P. A., Haskin, L. A.: Analysis for the rare-earth elements by neutron activation and Ge(Li) spectrometry. J. Radioanal. Chem., 6, 97-113 (1970).
- Eby, G. N.: Abundance and distribution of the rare-earth elements and yttrium in the rocks and minerals of the Oka carbonatite complex, Quebec. Geochim. Cosmochim. Acta 39, 597-620 (1975).
- Eckerman, H. von: The alkaline district of Alno Island: Sveriges geol. undersokning, no. 36, 176 pp. (1948).
- Faure, G., Powell, J. L.: Strontium Isotope Geology: New York, Springer-Verlag, 188 pp. (1972).
- Fenton, M. D., Faure, G.: The age of the igneous rocks of the Stillwater Complex of Montana. Bull. Geol. Soc. Amer. 80, 1599-1604 (1969).
- Fenton, M. D., Faure, G.: Rb-Sr whole-rock age determinations of the Iron Hill and McClure Mountain carbonatite-alkalic complexes, Colorado. The Mountain Geologist 7, 268-275 (1970).
- Flanagan, F. J.: U. S. Geological Survey standards-II. First compilation of data for the new U. S. G. S. rocks. Geochim. Cosmochim. Acta 33, 81-120 (1969).
- Gary, M., McAfee, R., Wolf, C. L. (Eds.): Glossary of Geology. Washington D. C.: Amer. Geol. Inst. (1972).
- Gast, P. W.: Trace element fractionation and the origin of tholeiitic and alkaline magma types. Geochim. Cosmochim. Acta 32, 1057-1086 (1968).
- Gold, D.: Average chemical composition of carbonatites. Econ. Geol. 58, 988-991 (1963).

- Green, D. H.: Contrasting melting relations in a pyrolite upper mantle under mid-oceanic ridge, stable crust and island arc environment. *Technophysics* 17, 285-297 (1973).
- Green, D. H., Ringwood, A. E.: The genesis of basaltic magmas. *Contrib. Min. Petrol.* 15, 103-190 (1967).
- Haskin, L. A., Allen, R. O., Helmke, P. A., Paster, T. P., Anderson, M. R., Korotev, R. S., and Zweifel, K. A.: Rare earths and other trace elements in Apollo 11 lunar samples. *Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 1*, vol. 2, 1213-1231 (1970).
- Haskin, L. A., Frey, F. A., Wildeman, T. R.: Relative and absolute terrestrial abundances of the rare earths. In: *Origin and Distribution of the Elements*, Ahrens, L. H., Ed., Intern. Ser. Monographs Earth Sc. 30, 889-912 (1968).
- Heinrich, E. W.: The geology of carbonatites. Chicago: Rand McNally, 555 pp. (1966).
- Heinrich, E. W., Anderson, R. J.: Carbonatites and alkalic rocks of the Arkansas River area, Fremont County, Colorado. *Mineralog. Soc. India I. M. A. volume*, 37-44 (1966).
- Holmes, A.: The potash ankaratrite-melaleucitite lavas of Nabugando and Mbuga craters, southwest Uganda, *Geol. Soc. Edinburgh Trans.* 15, 187-213 (1952).
- Hyndman, D. W.: Petrology of igneous and metamorphic rocks. New York: McGraw-Hill Book Company, 533 pp. (1972).
- Ingamells, C. O., Suhr, H. G.: Chemical and spectrochemical analysis of standard carbonate rocks. *Geochim. Cosmochim. Acta* 31, 1347-1350 (1967).
- Kay, R. W., Gast, P. W.: The rare earth content and origin of alkali-rich basalts. *Jour. Geol.* 81, 653-682 (1973).
- King, B. C., Sutherland, D. S.: Alkaline rocks of east and south Africa, Parts I, II, and III. *Sci. Prog.* 48, 298-321, 504-524, 709-720 (1960).
- King, B. C., Sutherland, D. S.: The carbonatite complexes of eastern Uganda. In: *Carbonatites*, Tuttle, O. F., and Gittins, J., Eds., New York: John Wiley and Sons, 73-126 (1966).
- Koster van Groos, A. F., Wyllie, P. J.: Liquid immiscibility in the system $\text{NaAlSi}_3\text{O}_8(\text{Ab})-\text{CaAl}_2\text{Si}_2\text{O}_8(\text{An})-\text{Na}_2\text{CO}_3-\text{H}_2\text{O}$. *Geol. Soc. Amer. Spec. Paper* 76, 172 (1964).

- Koster van Groos, A. F., Wyllie, P. J.: Liquid immiscibility in the system $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{CO}_2$ at pressures to 1 kb. *Amer. Jour. Sci.* 264, 234-255 (1966).
- ____ Liquid immiscibility in the join $\text{NaAlSi}_3\text{O}_8-\text{Na}_2\text{CO}_3-\text{H}_2\text{O}$ and its bearing on the genesis of carbonatite. *Amer. Jour. Sci.* 266, 932 (1968).
- ____ Liquid immiscibility in the join $\text{NaAlSi}_3\text{O}_8-\text{CaAlSi}_2\text{O}_8-\text{Na}_2\text{CO}_3-\text{H}_2\text{O}$. *Amer. Jour. Sci.* 273, 465 (1973).
- Koster van Groos, A. F.: The distribution of Sr between coexisting silicate and carbonate liquids at elevated pressures and temperatures. *Geochim. Cosmochim. Acta* 39, 27-34 (1975).
- ____ The effect of high CO_2 pressure on alkalic rocks. *Amer. Jour. Sci.* 275, 163-185 (1975).
- Lee, M.: Clay mineralogy of the Havensville Shale. M. S. Thesis, Kansas State Univ., 109 pp. (1972).
- Loubet, M., Bernat, M., Javoy, M., Allegre, C. J.: REE contents in carbonatites. *Earth Planet. Sci. Lett.* 14, 226-232 (1972).
- Methot, R.: Internal geochronologic study of two large pegmatites, Conn. Ph. D. Thesis, Kansas State Univ., 123 pp. (1973).
- Mineyev, D. A., Dikov, Yu P., Sobolev, B. P., Borutskaya, V. L.: Differentiation of REE under supercritical conditions. *Geochem. Int.* 3, 357-359 (1965).
- Mitchell, R. H., Brunfelt, A. O.: REE geochemistry of the Fen alkaline complex, Norway. *Contrib. Min. Petrol.* 52, 247-259 (1975).
- Parker, R. L.: Preliminary report on alkalic intrusive rocks in northern Wet Mountains, Colorado. U. S. Geol. Survey Prof. Paper 450-E, art. 181, E8-E10 (1963).
- Philpotts, J. A., Schnetzler, C. C., Thomas, H. H.: Petrogenetic implications of some new geochemical data on eclogitic and ultrabasic inclusions. *Geochim. Cosmochim. Acta* 36, 1131-1166 (1972).
- Powell, J. L., Hurley, P. M., Fairbairn, H. W.: Strontium isotopic composition and origin of carbonatites. In: Carbonatites, Tuttle, O. F., and Gittins, J., Eds., New York: John Wiley and Sons, 365-378 (1966).

- Reid, J. B., Frey, F. A.: Rare earth distributions in lherzolite and garnet pyroxenite xenoliths and the constitution of the upper mantle. *Jour. Geophys. Res.* 76, 1184-1196 (1971).
- Rock, N. M. S.: The role of CO_2 in alkali rock genesis. *Geol. Magazine* 113, 97-113 (1976).
- Schnetzer, C. C., Philpotts, J. A.: Partition coefficients of rare-earth elements between igneous matrix material and rock-forming mineral phenocrysts-II. *Geochim. Cosmochim. Acta* 34, 331-340 (1970).
- Shand, S. J.: Limestone and the origin of feldspathoid rocks. *Geol. Magazine* 67, 415-427 (1933).
- Shapiro, L., Brannock, W. W.: Rapid analyses of silicate, carbonate and phosphate rocks. *U. S. Geol. Survey Bull.* 1144-A, A1-A56 (1962).
- Shaw, D. M.: Trace element fractionation during anatexis. *Geochim. Cosmochim. Acta* 34, 237-243 (1970).
- Shawe, D. R., Parker, R. L.: Mafic-ultramafic layered intrusion at Iron Mountain, Fremont County, Colorado. *U. S. Geol. Survey Bull.* 1251-A, A1-A28 (1968).
- Sorensen, H.: Alkali syenites, feldspathoidal syenites, and related lavas. In: *The Alkaline Rocks*, Sorensen, H., Ed., New York: John Wiley and Sons, 22-52 (1974).
- Tuttle, O. F., Gittins, J. (Eds.): *Carbonatites*. New York: John Wiley and Sons, 591 pp. (1966).
- Watkinson, D. H.: Experimental studies bearing on origin of alkalic rock-carbonatite complex and Nb mineralization at Oka, Quebec. *Can. Mineral.* 10, 350-361 (1970).
- Watkinson, D. H., Wyllie, P. J.: The limestone assimilation hypothesis. *Nature* 204, 1053-1054 (1964).
- ____ Phase equilibrium studies bearing on the limestone assimilation hypothesis. *Bull. Geol. Soc. Amer.* 80, 1565-1576 (1969).
- ____ Experimental study of the composition join NaAlSiO_4 - CaCO_3 - H_2O and the genesis of alkalic rocks-carbonatite complexes. *Jour. Pet.* 12, 357-378 (1971).

- Wyllie, P. J.: Limestone assimilation. In: The Alkaline Rocks, Sorensen, H., Ed., New York: John Wiley and Sons, 459-473 (1974).
- Wyllie, P. J., Haas, J. L.: Melting relationships with excess vapor at 1 kb pressure. *Geochim. Cosmochim. Acta* 29, 871-892 (1965).
- _____. The system $\text{CaO-SiO}_2\text{-CO}_2\text{-H}_2\text{O}$ II. The petrogenetic model. *Geochim. Cosmochim. Acta* 30, 525-543 (1966).
- Wyllie, P. J., Huang, W.: Carbonation and melting reactions in the system $\text{CaO-MgO-SiO}_2\text{-CO}_2$ at mantle pressures with geophysical and petrological applications. *Contrib. Min. Petrol.* 54, 79-107 (1976).
- Wyllie, P. J., Tuttle, O. F.: The system $\text{CaO-CO}_2\text{-H}_2\text{O}$ and the origin of carbonatites. *Jour. Pet.* 1, 1-46 (1966).
- Wyllie, P. J., Watkinson, D. H.: Phase equilibrium studies bearing on genetic links between alkaline and subalkaline magmas. *Can. Mineral.* 10, 362-374 (1970).

RARE EARTH ELEMENTS DISTRIBUTIONS AND
STRONTIUM ISOTOPE DATA FROM THE GEM PARK IGNEOUS COMPLEX, COLORADO

by

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ABSTRACT

Major element analyses and initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios determined for the ultramafic-mafic rocks and carbonatites from the Gem Park complex, Colorado suggest the possibility of a comagmatic origin for these rock types. Initial Sr isotopic ratios for the gabbro and pyroxenite (0.7027 and 0.7028, respectively) are lower than those of the carbonatites (0.7036-0.7056) and the nepheline syenite pegmatite (0.7038), but they can still be considered similar within the limits of analytic precision (± 0.001) with one exception. Carbonatite, GP-9a&b, has a significantly higher initial Sr ratio (0.7056) than the other alkaline rocks and carbonatites. This probably indicates a slight difference in the isotopic composition of the source.

Based on the REE (rare earth element) concentrations which were determined by radiochemical neutron activation analysis, it can be shown that all the rock types in the Gem Park complex excluding the gabbros can be derived as either cumulates or residual melts from a hypothetical alkali basalt parent magma formed by 0.8-1.7 per cent partial melting of peridotite in the upper mantle.

Cumulate pyroxenite, GP-6, crystallized from the primary alkali basalt magma. After extensive crystallization (85-90 per cent) of phases such as olivine, plagioclase, and clinopyroxene in the proportion, 5:10:85, the alkali basalt produced a residual liquid with a REE distribution similar to those of natural ijolites.

The hypothetical ijolitic melt crystallized cumulate pyroxenite, GP-3, and after extensive crystallization (80 per cent) of apatite and

clinopyroxene in the proportion of 10:90 formed the nepheline syenite pegmatite as a residual liquid.

The carbonatites could have formed either by partial fusion of the same peridotite that produced the alkaline rocks with CO_2 at a depth greater than 80 km (Wyllie and Huang, 1976) or as immiscible liquid fractions from the hypothetical ijolitic melt at great depth (Cullers et al., 1976).

The gabbros are not related as a cumulate or residuum to the liquid line of descent from the hypothetical alkali basalt to the residual nepheline syenite liquid. However, the gabbros could have formed by further melting (4-6 per cent) of the same peridotite that produced the hypothetical alkali basalt magma.