K-Ar AGE OF THE CARBONATITE COMPLEX, OKA, QUEBEC

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ABSTRACT

The Cretaceous Oka carbonatite complex is intrusive into Precambrian gneisses and anorthosites. The K-Ar isochron age, based on 28 determinations on 22 samples from 7 intrusive units, is 117 m.y. The mica, whole-rock, and nepheline K-Ar isochron ages are 120, 125 and 127 m.y. respectively. Twelve dates on micas from 5 units fall between 102 and 120 m.y. and the mean mica age is 114 ± 4 m.y. Younger individual mica ages are interpreted as reflecting later redistribution of potassium, cooling period of the magma, or both. The chronology of the intrusive units could not be resolved on the basis of the mica ages. Monticellite (176), melilite (155, 162), nosean (210), pyroxene (341) and apatite (1074) yield larger apparent ages because they contain excess argon–40. The complex or its parent magma was probably derived from the mantle and crystallized in presence of argon–40, derived from heating and fenitization of the Precambrian wall-rocks.

INTRODUCTION

The Oka complex is part of the Monteregian petrographic province, a group of igneous intrusions lying along an arc extending for about 140 miles from Oka through Montreal to the Western Appalachians (Adams, 1903 ; Graham, 1944 ; Pouliot, 1962 ; Gold, 1963). The geology, petrology, structure and geochemistry of the complex have been discussed by Rowe (1958) ; Maurice (1957) ; Davidson (1963) ; and Gold (1963, 1966). Gold (1963) mapped the complex in detail and compiled its geology.

The Oka complex is a double-ring structure with an oval outline, 4.5 x 1.5 miles, with the major axis trending northwest (Fig. 1). It is intrusive into a Precambrian inlier which consists of gneisses and anorthosites of the Grenville structural province. An oval-shaped carbonatite core under-lies more than half the surface area and is enclosed by crescentic tabular masses and rink-dykes of ultramafic alkalic rocks. Gold (1963, 1966, 1969) recognized at least 7 carbonatite units. They consist of medium- to coarse-grained calcite rocks with variable amounts of apatite, magnetite, biotite, pyroxene, melilite, monticellite, melanite, and niocalite as accessory minerals. The units commonly occur in the form of bands concentric with the margins of the complex, or as arcuate tabular bodies.

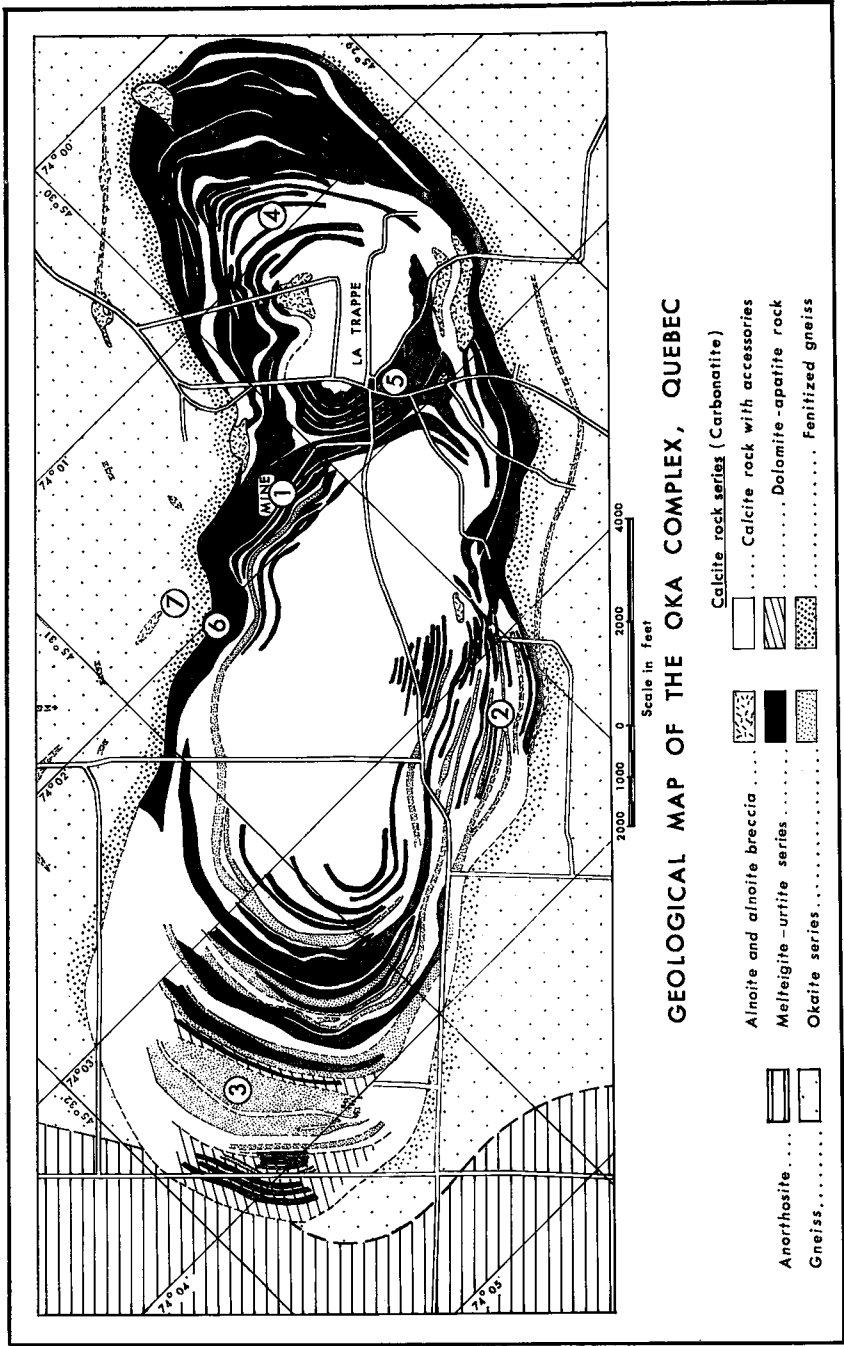* Present address : University of Arizona, Tucson, Arizona, U.S.A.

GEOLOGICAL MAP OF THE OKA COMPLEX, QUEBEC

Alnoite and alnoite breccia ....

Melteigite–urtite series ....

Okaite series ....

Anorthosite ....

Gneiss ....

Calcite rock series (Carbonatite)

.... Calcite rock with accessories

.... Dolomite–apatite rock

.... Fenitized gneiss

MINE

LA TRAPPE

Scale in feet

2000 1000 0 2000 4000

Fɪɢ. 1. Geology of the Oka carbonatite complex, Quebec (after Gold, 1963). Circled numbers refer to sample locations.

The ultramafic alkalic rocks occur as ring dykes or as arcuate dykes that mainly surround the calcite core. They have been broadly grouped by Gold (1963) as follows :

(a) Okaite-jacupirangite series, characterized by the presence of melilite, haüyne, titanaugite, magnetite and nepheline in varying proportions.

(b) An ijolite-urtite series, with nepheline and sodic pyroxene as the main constituents.

(c) Lamprophyric rocks. Alnoite dykes, plugs and breccia pipes are common in both the complex and the surrounding country rocks, and represent the final phase of intrusive activity.

Sulphide and fluorite veins follow joint planes and faults. Zones of hydrothermal alteration and intense biotitization that resulted from late stage potassium metasomatism, are found within the silicate rocks. These replacement rocks consist mainly of calcite and biotite with minor magnetite, pyrochlore and sulphides. Potassium metasomatism is not the only form of hydrothermal alteration in the complex : serpentine is developed in monticellite-bearing rocks, vesuvianite, wairakite and zeolite minerals in the melilite bearing rocks, and zeolitic minerals in feldspathic rocks (Gold, 1969).

Twenty-eight K-Ar ages on 22 samples from the complex were determined in an attempt to :

(a) date and separate the major episodes of intrusive activity at Oka.

(b) postulate the source of carbonatite magma on the basis of the distribution of argon in cogenetic minerals and whole-rock samples.

Sampling and analytical procedure

Three carbonatite units, okaite, urtite, alnoite and the replacement rocks were sampled (Fig. 1). The pyroxene carbonatite (1) and monticellite carbonatite (1) are from the open-pit of the St. Lawrence Columbium and Metals Corporation. The niocalite carbonatite (2) sample is from trench No. 4 in the Bond zone, biotite from the replacement rock (2) is from a trench on the Bond zone, the nepheline okaite (3) is from Husereau Hill, the microurtite (4) from an outcrop in the southern ring, and alnoite (5) was collected in a road cut west of the Monastery.

The analytical procedure and error calculations used in the Geochronology laboratory, Carleton University have been described by Shafiqullah (1969). Briefly, argon was determined on an A.E.I. MS 10 mass spectrometer operated statically using argon-38 as a spike. Potassium was

determined in duplicate by flame photometry and the average used. The age calculations are based on the following constants :

$$\lambda_e = 0.585 \times 10^{-10} \; {}_{yr}^{-1}$$
$$\lambda = 5.30 \times 10^{-10} \; {}_{yr}^{-1}$$
$$K^{40}/K = 0.0119 \text{ atom per cent.}$$

Presentation of data

Analytical data and K-Ar ages for samples from the Oka complex are presented in Table 1, and on two isochrons

(a) log argon-40 (radiogenic) vs. log K_2O (Fig. 2)

(b) Ar^{40}/Ar^{36} vs. K^{40}/Ar^{36} (Fig. 3).

(a) The K-Ar isochron concept, introduced by Livingston and others (1967), allows a wide range of data to be graphically compared. Log argon-40 (radiogenic) in moles is plotted against log K_2O (weight per cent). It is, in effect, a plot of argon-40 versus potassium-40 and the data for a particular age fall in a straight line with unit slope.

$$Ar_r^{40} = a \, K^{40} \, (e^{\lambda t} - 1)$$
$$= ab \, K_2O \, (e^{\lambda t} - 1)$$
$$\log Ar_r^{40} = \log K_2O + \log (ab) + \log (e^{\lambda t} - 1)$$

where $a = \lambda_e/\lambda = \text{constant}$

$b = K^{40}/K_2O = \text{constant}$, ($K_2O$ in weight per cent)

$r = \text{radiogenic argon-40}$

If time t is specified, $\log (e^{\lambda t} - 1)$ is a constant.

Hence, $\log Ar_r^{40}$ vs. $\log K_2O$ is a straight line of unit slope.

(b) The K-Ar isochron presented in Fig. 3 is a plot of Ar^{40}/Ar^{36} against K^{40}/Ar^{36} on cartesian coordinates. Ar^{40}/Ar^{36} indicates the ratio of the measured isotopes, where argon-40 includes radiogenic argon-40, air argon–40 and excess argon–40, if any. Ar^{40}/Ar^{36} in air argon is 295.6 (Nier, 1950). Some argon-36 is always present : it may originate from the argon extraction and purification line, mass spectrometer, mineral or rock sample. If the system remained closed to loss or gain of argon-40 and potassium, data from a suite of coeval rocks would lie on a straight line (McDougall and Stipp ; 1969) of the form :

$$y = mx + c$$

where $y = (Ar^{40}/Ar^{36})t$

$$x = (K^{40}/Ar^{36})t$$

$$c = (Ar^{40}/Ar^{36})_o + (Ar^{40}/Ar^{36})_{air}$$

$$m = e^{\lambda t} - 1), = \text{consant, when t is specified.}$$

$$m = \text{decay constant}$$

$(Ar^{40}/Ar^{36})_o = $ the ratio at closure,

$(Ar^{40}/Ar^{36})_{air} = 295.6$, air argon ratio.

TABLE 1. K-AR AGES AND ANALYTICAL DATA FOR SAMPLES FROM THE CARBONATITE COMPLEX AT OKA, QUEBEC.

| Sample Location	Rock Type	Sample Type	Mesh size	K_2O Weight per cent	Ar_r^{40} per cent	Ar_r^{40} p.p.m.	Date in m.y.
1	Monticellite carbonatite	Mica	35–18	8.173	85	0.058178	117 ± 6
		"	60–35	8.219	49	0.058244	116 ± 7
		"			24	0.056646	113 ± 11
		Monticellite	35–18	0.024	13	0.000261	176 ± 31
		Whole rock	35–18	1.233	39	0.010849	143 ± 10
1	Pyroxene carbonatite	Mica	+ 18	9.274	66	0.062494	111 ± 6
		"	35–18	8.533	74	0.060345	116 ± 6
		Pyroxene	35–18	0.074	25	0.001639	341 ± 34
		Whole rock	35–18	0.101	38	0.001901	276 ± 22
		"	"	"	31	0.001727	268 ± 23
2	Niocalite carbonatite	Melilite	35–18	0.142	7	0.00136	155 ± 48
		Apatite	35–18	0.008	4	0.000671	1074 ± 444
3	Okaite	Mica	100–60	8.472	83	0.057054	111 ± 6
		Nepheline	100–60	4.305	43	0.035088	133 ± 8
		Nosean	100–60	1.386	26	0.019652	236 ± 20
		"	"	"	16	0.016881	196 ± 26
		Melilite	100–60	0.124	7	0.001233	162 ± 49
		Whole rock	− 100	1.625	22	0.012508	126 ± 9
4	Urtite	Nepheline	100–60	6.497	57	0.046097	116 ± 6
					64	0.053937	136 ± 7
		"	200–150	2.231	77	0.017308	127 ± 6
5	Alnöite	Mica	100–60	8.927	67	0.058510	108 ± 6
		"	"	"	72	0.056769	105 ± 5
		"	35–18	8.958	66	0.06406	117 ± 7
		"	60–35	9.108	74	0.063718	115 ± 6
2	Replacement rock	"	+ 18	9.453	93	0.069355	120 ± 6
		"	35–18	9.369	85	0:063804	112 ± 6
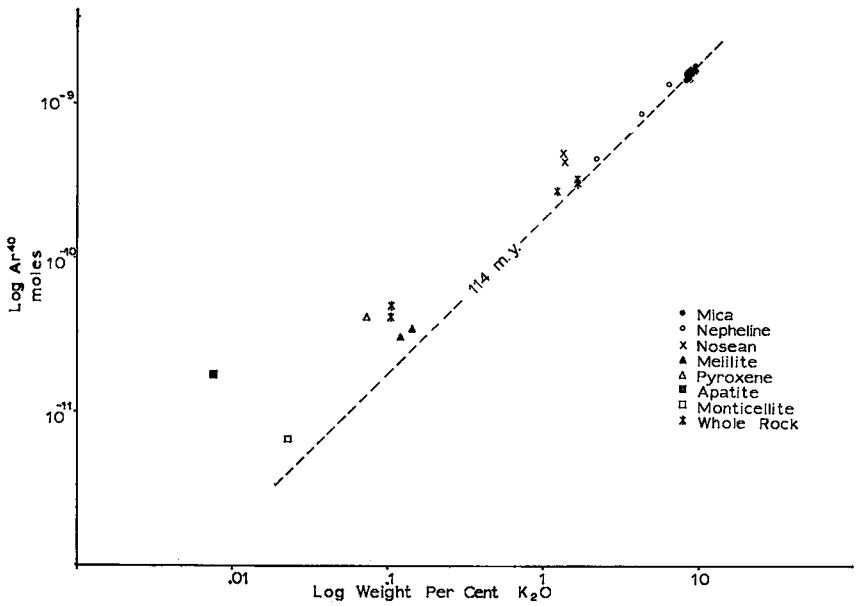
FIG. 2. K-Ar isochron : log Ar^{40} (radiogenic) vs. log K_2O. 114 m.y. isochron with unit slope is the mean of 12 mica ages.
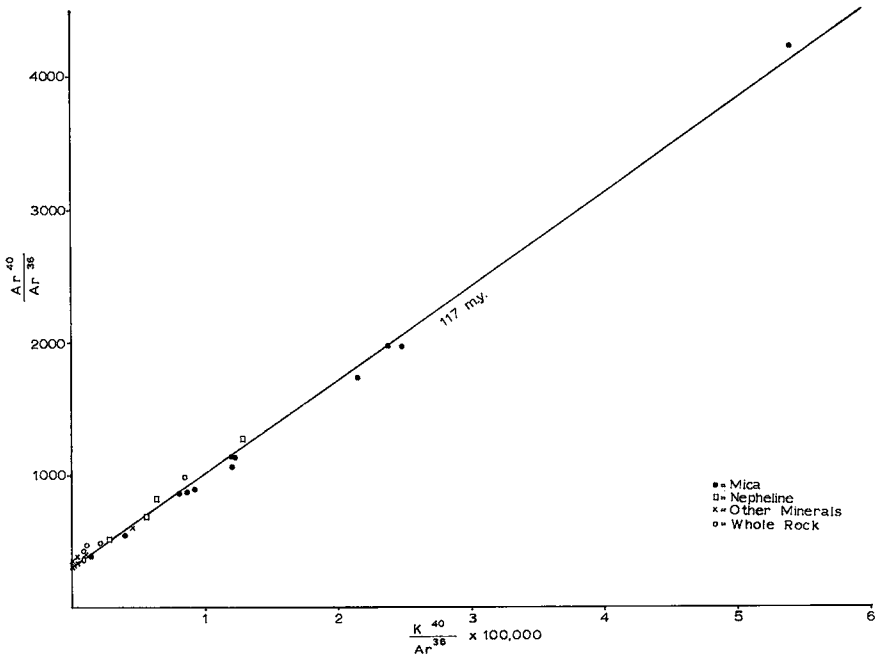

FIG. 3. K-Ar isochron : Ar^{40}/Ar^{36} vs. K^{40}/Ar^{36}. The solid line is the regression line of mica points.

The age, t, of the sample is a function of slope m, according to the equation :

$$t = \frac{1}{\lambda} \ln \left(1 + \frac{\lambda}{\lambda_e} \cdot \frac{Ar^{40}}{K^{40}}\right)$$

$$= \frac{1}{\lambda} \ln \left(1 + \frac{\lambda}{\lambda_e} \cdot m\right)$$

The following three assumptions are made :

(i)   the samples in question have the same age

(ii) the samples had a common $(Ar^{40}/Ar^{36})_0$ ratio

(iii) the samples have remained closed systems for both K^{40} and Ar^{40} since time t = o.

If no radiogenic argon-40 was present at the time of closure or crystallization of the minerals, $(Ar^{40}/Ar^{36})_0$ would reflect the air argon ratio. The isochron would intersect the Ar^{40}/Ar^{36} axis at 295.6, the origin for K-Ar systems. An intercept smaller than 295.6 suggests either potassium metasomatism or preferential loss of argon relative to potassium. An intercept larger than 295.6 indicates excess argon or preferential loss of potassium relative to argon from the system. Excess argon-40, as used in this paper is a general term and includes transient argon-40, inherited argon-40, and extraneous argon-40 (Damon and others, 1968).

The isochron is a helpful visual aid in examining data for samples with low K_2O, geologically young samples, or both. These samples have relatively low radiogenic argon-40 enrichment and high air argon contamination (York, Baksi and Aumento, 1969). In such a case, the large argon-36 peak can be precisely measured. In addition, the assumption of initial ratios is avoided.

Discussion of data on the Oka complex

Twelve mica ages on ten samples from 5 of the intrusive units recognized by Gold (1963) range between 105 and 120 m.y. It is not possible to establish a chronology of the units on the basis of the mica ages (Figs. 2, 3). The mean of the 12 mica ages is 114 ± 4.5 m.y. and is in remarkable agreement with 114 ± 7 m.y., the mean of 3 Rb-Sr ages on micas from the complex (Fairbairn, and others, 1963). However, they used the decay constant :

$$\lambda = 1.47 \times 10^{-11} \, yr^{-1}$$

instead of

$$\lambda = 1.39 \times 10^{-11} \, yr^{-1}$$

which is now in general use and preferred by the authors. Using the second value, the mica Rb-Sr age is 121 m.y.

An apparent relationship exists between age and grain size. The coarser-grained fraction yields older ages. However, mica from the pyroxene carbonatite is an exception.

The 114 m.y. line with unit slope (Fig. 2) indicates the mean of 12 mica ages. The micas have a similar K content and are clustered together. Nosean, pyroxene, apatite and melilite fall above the mica line, indicating that they either formed much earlier than mica or contain excess argon-40.

In the K-Ar isochron (Fig. 3) most of the points other than mica cluster together at low concentrations, indicating a high air-argon contamination and low K content, or both. The mean of the regressions of Ar^{40}/Ar^{36} on K^{40}/Ar^{36} and K^{40}/Ar^{36} on Ar^{40}/Ar^{36}, of all the 28 determinations ($Ar^{40}/Ar^{36} = 0.00705$. $K^{40}/Ar^{36} + 311$) gives an isochron age of 117 m.y. The values of the constants for the two regression equations do not differ by more than 0.3 per cent of the mean.

The mica data fall on or near a line with an apparent age of 120 m.y. which intersects the Ar^{40}/Ar^{36} axis at 243, instead of 295.6 (Fig. 4). The regression lines of Ar^{40}/Ar^{36} on $K^{40}Ar/^{36}$ and K^{40}/Ar^{36} on Ar^{40}/Ar^{36} differ by 0.1 per cent from the mean for the micas. The equation for the regression line (Fig. 4) is :

$$Ar^{40}/Ar^{36} = 0.00725 \ K^{40}/Ar^{36} + 243$$

An intercept smaller than 295.6 indicates potassium metasomatism and preferential loss of existing radiogenic argon-40 relative to potassium when the mica K-Ar geochronometer was reset, or both. Two types of micas are recognized : mica from carbonate units is commonly green with or without a brown rim and mica from silicate units is pale red-brown with color-zoning towards green at the edges. The analysed micas include both types ; however, their Ar^{40}/K^{40} ratios are not distinctive.

The difference between the K-Ar age and Rb-Sr age of individual mica may also reflect a slow, uniform cooling of the rocks. A similar cooling period was noted by Armstrong, Jaeger and Eberhardt (1966) in the Alps.

The arithmetic mean of 4 nepheline ages is 128 m.y. (Table 1). Unfortunately, the samples are somewhat altered to nosean, natrolite and analcine which have open structures, and effective ion exchange properties similar to zeolites. The nepheline isochron ($Ar^{40}/Ar^{36} = 0.00769$ $K^{40}/Ar^{36} + 297$) age is 127 m.y. (Fig. 4).

Five "whole-rock" analyses of the carbonate-free fraction of pyroxene carbonatite, monticellite carbonatite and okaite show considerable scatter. Calcite was removed because analysed samples contain negligible ($<.005$
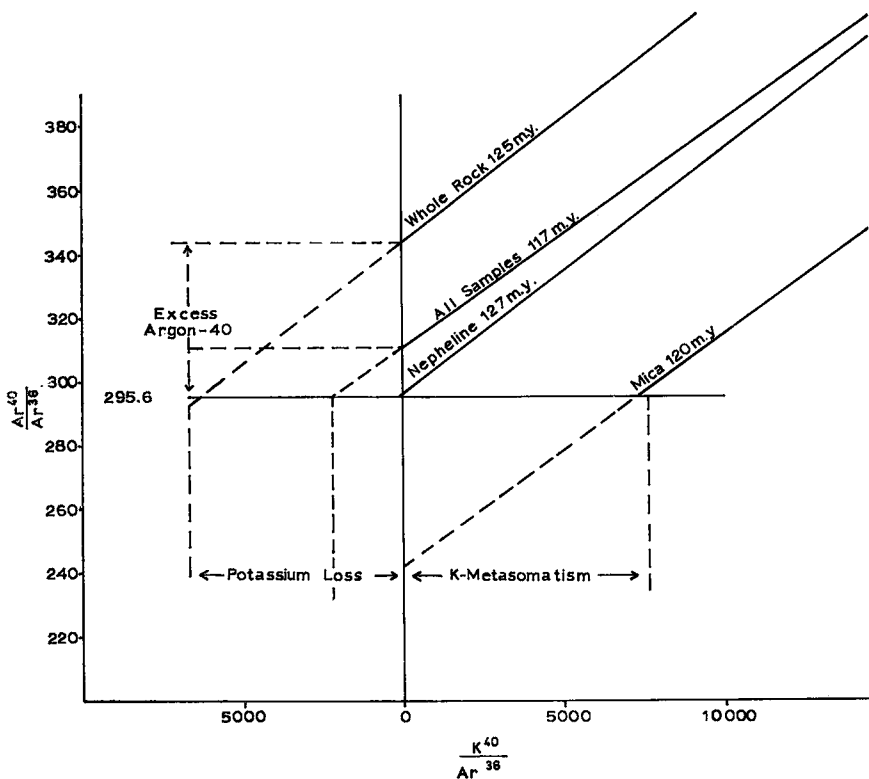
FIG. 4. The intercepts of the isochrons on the Ar^{40}/Ar^{36} axis in Ar^{40}/Ar^{36} vs. K^{40}/Ar^{36} plot, and their significance.

per cent) potassium. Nevertheless, the regressions of $Ar^{40}Ar/^{36}$ on K^{40}/Ar^{36} and K^{40}/Ar^{36} on Ar^{40}/Ar^{36} are similar, within 1.3 per cent of the mean. The isochron $(Ar^{40}/Ar^{36} = 0.00756\ K^{40}/Ar^{36} + 345)$ with 125 m.y. age intersects the ordinate at 345, indicating preferential leaching of potassium relative to argon during hydrothermal alteration, excess argon-40 in the constituent minerals, or both.

Apatite, monticellite, melilite, pyroxene and nosean have larger ages and cluster together in Fig. 3 but show considerable scatter in Fig. 2. The minerals have low K contents. The scatter of the data may reflect experimental error, differing times of formation of the minerals in the magma chamber, variable excess argon-40 in them, either in inclusions or in the occluded state or any combination of these. Of these possibilities, only the magnitude of excess argon-40 in the constituent minerals is adequate to explain the scatter. Variable loss of potassium from this group of minerals

is excluded on the ground that the original K content is unlikely to have been high enough to place them on an isochron passing through 295.6 on the Ar^{40}/Ar^{36} axis.

Age of the Oka complex

The Oka complex has not undergone any known major tectonic disturbance since the Cretaceous. If the system remained closed to loss or gain of argon-40 similar ages on coexisting minerals would be expected.

The mica, whole-rock and nepheline K-Ar isochron ages are 120, 125 and 127 m.y. respectively. The mica Rb-Sr age is 121 m.y. There are two alternative interpretations on the age of the complex :

(a) The whole-rock and nepheline isochron ages indicate that the complex was emplaced about 125-127 m.y. ago. Nepheline retains argon at least as well as mica. The mica ages represent the time of mica crystallization, late stage metasomatism, cooling time of the rocks, or any combination of these. However, the precision of the whole-rock and nepheline isochrons is limited by the small number of determinations.

(b) The complex was emplaced about 120 m.y. ago, on the basis of the mica K-Ar isochron and mica Rb-Sr ages. The micas have good argon retentivities and are considered age standards. The larger ages of the co-existing minerals and whole-rocks may be attributed to differentiation in a magma chamber in the presence of argon-40 and later emplacement, preferential loss of potassium or gain of argon by some of the constituent minerals during hydrothermal alteration processes, or both.

Source of carbonatite magmas

The origin and mode of emplacement of carbonatites are not known with certainty. Heinrich (1966), and Tuttle and Gittins (1966) have reviewed the different theories.

Argument is divided on whether the carbonate magma is derived from a silicate magma through some process of differentiation or is generated through assimilation of limestone, from metasomatism, or from rheomorphism of limestone.

David (1963) favoured assimilation of limestone by basic magma for the origin of the Oka complex, while Gold (1963, 1966) favoured a magmatic origin except for some of the metasomatic ijolites and the fenites. He considered that some of the ijolites might be fenitized wall-rocks, rheomorphosed and intruded during formation of the complex.

Together with the primitive initial Sr^{87}/Sr^{86} ratios for the rocks of the complex (Powell, 1966) the approximate agreement among the mica Rb-Sr

(121), mica K-Ar isochron (120), whole-rock K-Ar isochron (125) and nepheline K-Ar isochron (127) ages suggests that the carbonatite or its parent magma was derived from the mantle and has not assimilated significant amounts of argon-40 from crustal material. The excess argon in some of the rocks and minerals indicate that the carbonatite was produced by differentiation in the presence of argon-40. The whole-rock ages in the aureole range between 87 and 779 m.y. and tend to be older with distance from the complex (Shafiqullah, 1969), indicating that argon-40 has been removed from the wall-rock. Probably this argon was absorbed by the alkalic magma and incorporated in part by the crystallizing minerals.

Conclusion

The K-Ar isochron age of 28 determinations on 22 samples from the Oka complex is 117 m.y. whereas the mica, whole-rock and nepheline K-Ar isochron ages are 120, 125 and 127 m.y. respectively. The mica Rb-Sr age is 121 m.y. The intrusive units could not be distinguished chronologically on the basis of 12 mica ages (114 ± 4 m.y.) from 5 intrusive units.

The larger melilite, monticellite, pyroxene, apatite and nosean ages indicate these minerals formed in an environment containing argon-40 and occluded or trapped argon-40. The carbonatite or its parent was probably derived from the mantle. The argon-40 environment may have resulted from the heating and fenitization of the wall-rocks.

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