

Sm—Nd, K—Ar and petrologic study of some kimberlites from eastern United States and their implication for mantle evolution

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Abstract. We provide new data on Sm—Nd systematics, K—Ar dating and the major element chemistry of kimberlites from the eastern United States (mostly from central New York State) and their constituent mineral phases of olivine, clinopyroxene, garnet, phlogopite and perovskite. In addition, we report Nd-isotopes in a few kimberlites from South Africa, Lesotho and from the eastern part of China. The major element compositions of the New York dike rocks and of their constituent minerals including a xenolith of eclogite are comparable with those from the Kimberley area in South Africa. The K—Ar age of emplacement of the New York dikes is further established to be 143 Ma.

We have analyzed the Nd-isotopic composition of the following kimberlites and related rocks: Nine kimberlite pipes from South Africa and Lesotho, two from southern India; one from the U.S.S.R., fifteen kimberlite pipes and related dike rocks from eastern and central U.S. and two pipes from the Shandong Province of eastern China. The age of emplacement of these kimberlites ranges from 1300 million years to 90 million years. The initial Nd-isotopic compositions of these kimberlitic rocks expressed as $\varepsilon_{\text{Nd}}^{\text{l}}$ with respect to a chondritic bulk-earth growth-curve show a range between 0 and +4, with the majority of the kimberlites being in the range 0 to +2. This range is not matched by any other suite of mantle-derived igneous rocks. This result strengthens our earlier conclusion that kimberlitic liquids are derived from a relatively primeval and unique mantle reservoir with a nearly chondritic Sm/Nd ratio.

the lower mantle is essentially undifferentiated for Sm—Nd and Rb—Sr systems and that this lower mantle is overlain by a depleted mantle which is interpreted, in these models, to be residual after the extraction of the continental crust throughout the geologic history of the earth.

In 1978, we reported a study of Sm—Nd systematics of kimberlites and their mafic and ultramafic inclusions (Basu and Tatsumoto 1978). This study and our subsequent studies (Basu and Tatsumoto 1979, 1980) showed that the initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of kimberlites differed from their eclogitic and peridotitic inclusions, but were identical or close to the bulk earth chondritic ratio. Since the study by Boyd (1973), it has been known that ultramafic inclusions in kimberlites are derived from depths less than and up to 180 km in the mantle. In addition, it also follows from this study that kimberlitic magma must be derived from at least as great a depth as 180 km in the upper mantle. We have thus used the kimberlites and their inclusions as representatives of "natural drill-holes" in the mantle, and have constructed a Sm—Nd evolutionary model for the upper 200 km of the subcontinental mantle. In this model, the kimberlite's source was considered to be the most primitive, while, in contrast, the mafic and ultramafic inclusions in kimberlites showed both time-averaged Nd enrichment and depletion with respect to the chondritic Sm/Nd ratio.

In this article, we provide new data on Sm—Nd systematics, K—Ar dating and on the petrology of some kimberlite dike rocks from the eastern United States. In addition, we report Nd-isotopes in a few kimberlites from South Africa and Lesotho and from the eastern part of China. The purpose of this study is to establish the kimberlitic nature of the heretofore relatively unknown dikes of New York State, their time of emplacement and to compare their initial Nd isotopic ratios with those of other well-known kimberlites from different continents. Our primary goal in studying kimberlites is to explore the bearing that kimberlites may have on understanding mantle evolution, as outlined in an earlier contribution by Basu and Tatsumoto (1978).

Introduction

Recent Nd and Sr isotope studies on a variety of terrestrial igneous rocks have shown their derivation from depleted, enriched and primitive mantle reservoirs. Many of these studies are on young basaltic rocks which are considered to be uncontaminated partial melts from the upper mantle. These isotopic data in conjunction with data on basic and acid rocks of the Archean and the Proterozoic provided a basis for quantitative models of mantle evolution (O'Nions et al. 1979; Wasserburg and DePaolo 1979; Jacobsen and Wasserburg 1979). These models propose that

Kimberlite dikes of central New York State

General Geology

There are approximately 80 dikes and 2 diatremes of alkaline ultrabasic composition in central New York. The three major areas in the region in which these dikes occur are

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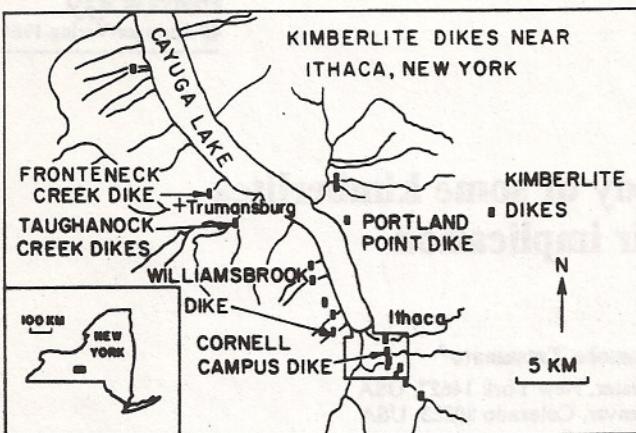


Fig. 1. Distribution of kimberlite dikes around Cayuga Lake in central New York, after Foster (1970) and Kay et al. (1983)

the southern part of Cayuga Lake, Syracuse area, and the Manheim area east of Syracuse. The field occurrences of most of these dikes have been described by Martens (1924), Foster (1970), Hogeboom (1958), and more recently summarized by Meyer (1976). These dikes are similar in shape, size, mode of occurrence and in their ultrabasic character to those in other parts of North America that cut across Paleozoic and Precambrian rocks in Quebec, Pennsylvania, Virginia, Tennessee, Kentucky, and Missouri.

The majority of 80 kimberlite dikes are located around Cayuga Lake, near Ithaca (Fig. 1). Five of these dikes were found in the city of Syracuse, one in Manheim east of Syracuse and one in Clintonville, 15 miles southwest of Syracuse. The exposures of the Syracuse area dikes were discovered in 1837 and are now inaccessible due to construction of city buildings. The samples of the Euclid Avenue and DeWitt dike of Syracuse and of the Clintonville and Manheim dikes were made available to us by Professor Gary Boone of Syracuse University. The other dikes of the Cayuga Lake region were sampled by us in the field (Fig. 1). The dikes intrude into the youngest rock in each area. In the Cayuga Lake area, the youngest rocks are middle to Upper Devonian shales and limestones with some intercalated beds of sandstones and salt (Kay et al. 1983). The thickness of these dikes varies from a few millimeters (in the Taughannock Creek near Ithaca) to several meters (Williams Brook and Portland Point). Most of these dikes occur as single intrusions, although multiple dikelets are observed in Portland Point and in the Taughannock Creek. In general, the strikes of these dikes are constant (almost north-south) and the dips are vertical to subvertical. The strikes of these dikes also conform to one of the north-south set of joints developed in the Upper Devonian shales of the Ithaca region.

In order to compare the Nd-isotopic data of the New York dikes, we have also analyzed kimberlitic rocks from three other regions in the eastern United States. These localities are: Elliot County, Kentucky; Avon, Missouri; Staunton, Virginia. Brief descriptions of these rocks are, therefore, in order and are given below.

Elliot County, Kentucky-Diller (1887) first described in detail the peridotite diatremes of eastern Kentucky in Elliot County. Inclusions of eclogite and granulite are common in these kimberlites. Zartman et al. (1967) reported K-Ar and Rb-Sr ages of 269 Ma for phlogopites from these

kimberlites. These authors, however, cautioned about a possible inherited age of these micas.

Avon, Missouri-Kimberlite dikes and diatremes were described by Weller and St. Clair (1928). The presence of Devonian fossils in limestone xenoliths within some of the diatremes indicates a post-Devonian age of emplacement. Petrologic and mineralogic data of olivine, pyroxene, phlogopite and spinel from these diatremes are similar to those from other known kimberlites (Mansker 1973; Meyer 1976). Zartman et al. (1967) reported concordant K-Ar and Rb-Sr ages of 390 Ma for micas from two diatremes which suggest a mid-Devonian age for their emplacement.

Staunton, Virginia - A group of alkalic dikes of nepheline syenite to peridotite composition occurs in Virginia and West Virginia (Dennison and Johnson 1971). The dikes appear to be associated with a north-south joint pattern similar to those in central New York. Zartman et al. (1967) analyzed biotite and hornblende from a nepheline syenite and considered a 149 Ma age of emplacement for this rock. We have included this nepheline syenite in the present study for comparison with the kimberlites, and also because Zartman et al. (1967) considered the age of this syenite to be essentially of the same age as those of the kimberlite dikes of New York.

Major element chemistry of the New York dikes

The major element chemistry of the New York dikes is shown in Table 1. The chemical analyses of the dikes are plotted in Fig. 2 in terms of $(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O})$, $(\text{CaO} + \text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3 + \text{TiO}_2)$, and volatiles as suggested by Dawson (1967) and compared with the range of composition shown by the South African kimberlites (Clement et al. 1979) from the Kimberley area. It is clear from Fig. 2 that the New York dikes are essentially similar in bulk chemical composition to the South African kimberlites. Although this triangular variation diagram does not differentiate between alnoite and kimberlite, it should be pointed out that an extensive search by us and by Kay et al. (1983) for the presence of melilite, a key mineral of alnoite, in the New York dike rocks revealed no melilite.

Brey (1978) postulated that kimberlites form a chemically continuous spectrum with olivine melilitites. Kimberlites have similar $\text{CaO}/\text{Al}_2\text{O}_3$, lower $\text{Al}_2\text{O}_3/\text{TiO}_2$, and higher $(\text{CaO} + \text{MgO})/\text{SiO}_2$ ratios, and an MgO/CaO ratio that is three to four times higher than in olivine melilitites. The chemistry of the New York dikes when compared with Brey's (1978) summary of the chemical data on world-wide occurrences of olivine melilitites shows that the $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio for the New York rocks is lower than that of olivine melilitites. The MgO/CaO ratio for the New York dikes is at least twice as high as the values for the olivine melilitites. Thus, the considerations of major element chemistry and the absence of melilite in the New York dikes suggest that these rocks are true kimberlites, a conclusion also supported by the recent report on the Ithaca, New York dikes by Kay et al. (1983).

Microprobe analyses of the constituent minerals in New York dikes

The microprobe analyses (Table 2) of olivine, phlogopite, perovskite, pyroxene and garnet from the kimberlite dikes were performed at the Lamont-Doherty Geological Obser-

Table 1. Major element and some trace element compositions of the kimberlite dikes of New York State

Sample number	E1	E9	J1	C1	M1	1	2	3	4	5	6
SiO ₂	34.24	35.37	34.81	25.30	35.35	33.38	26.37	33.20	33.0	27.0	30.0
Al ₂ O ₃	3.90	4.64	4.80	4.31	6.10	5.09	6.14	4.45	3.75	3.72	2.90
Fe ₂ O ₃	4.08	5.28	5.70	3.27	8.53	11.21 ^a	8.43 ^a	9.55 ^a	11.50 ^a	10.6	9.86
FeO	5.34	4.45	3.22	5.08	5.60	—	—	—	—	—	—
MgO	28.91	27.94	28.27	15.60	20.40	23.78	16.19	28.19	23.60	12.7	21.4
CaO	10.13	6.38	4.95	18.99	7.40	9.06	16.01	6.60	12.0	19.0	14.3
Na ₂ O	0.19	0.15	0.12	0.24	0.70	0.44	1.46	3.38	0.37	0.24	0.23
K ₂ O	1.19	2.41	2.03	0.80	2.88	3.19	0.46	0.43	2.87	1.68	1.08
H ₂ O ⁺	6.44	7.16	8.85	4.96	10.15	7.61	11.42	7.50	3.40	7.61	9.21
H ₂ O ⁻	0.66	0.84	1.13	3.20	—	—	—	—	—	—	—
CO ₂	2.06	2.18	3.46	13.78	—	3.41	10.70	8.76	6.34	14.64	9.70
TiO ₂	1.45	1.60	1.15	1.43	2.25	2.52	1.98	1.59	2.65	1.78	1.72
P ₂ O ₅	0.39	0.45	0.36	0.74	—	0.44	1.12	0.35	—	—	—
Cl	0.12	0.06	0.05	0.00	—	—	—	—	—	—	—
Cr ₂ O ₃	0.24	0.25	0.24	0.23	—	—	—	—	—	—	—
MnO	0.17	0.17	0.15	0.26	—	0.17	0.19	—	0.18	0.31	0.21
SrO	0.05	0.07	0.06	0.07	—	—	—	—	0.10	0.19	0.13
BaO	0.12	0.13	0.16	0.56	—	0.09	—	—	0.18	0.17	0.17
NiO	0.15	0.13	0.14	0.09	—	—	—	—	—	—	—
Total	99.96	99.88	99.71	100.20	99.26	100.39	100.47	104.00	99.94	99.64	100.91

E1, E9 = Syracuse Green Street Dikes; J1 = Syracuse Euclid Avenue Dike; C1 = Clintonville Dike; M1 = Manheim Dike; 1 to 6 = are New York State Kimberlite Dikes from the Ithaca area. Sources of data: Hogeboom (1958), Foster (1970), and Boone (1979)

^a (Total iron as Fe₂O₃)

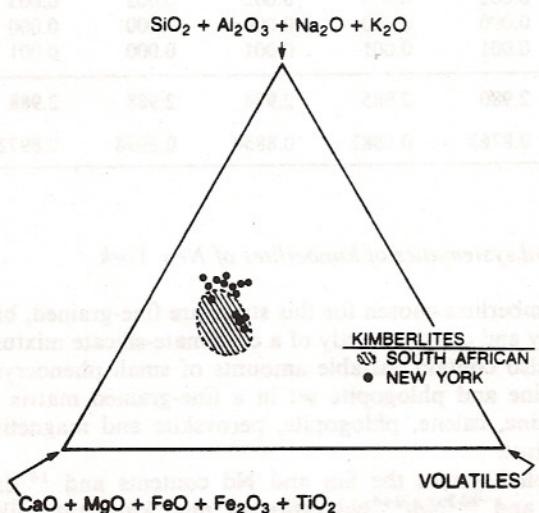


Fig. 2. A ternary plot of the major oxides of the kimberlite dikes of New York compared with the general range of major elemental compositions of kimberlites from the Kimberley area (Clement et al. 1979). Sources of the New York kimberlite dike data are: Hogeboom (1958); Boone (unpubl., pers. comm.) and Foster (1970)

vatory with an automated ARL microprobe (Rubury 1981). Kay et al. (1983) have provided a detailed mineralogical account of the various phases in the Ithaca kimberlites. We have attempted to provide a set of representative analyses of the minerals and describe here some of the salient aspects of these analyses. Specimens of strained (kink banded) and unstrained euhedral and anhedral olivines were analyzed. The compositions of these olivines vary from Fo 87.6 to Fo 91.5. Strained olivine crystals tend to show

a lower forsterite content than unstrained grains. Although most of the analyzed olivines have compositions similar to olivines from peridotite xenoliths, we believe many of the unstrained olivine crystals with lower forsterite contents are true phenocrysts in the kimberlite. There are no significant differences in chemical composition between unstrained and strained phlogopites in individual dike samples although there is considerable variation in FeO, MnO, MgO, and Na₂O contents in phlogopites from various dikes. Most of these phlogopites are similar to the groundmass phlogopites of South African kimberlites (Kay et al. 1983) as reported by Smith et al. (1978). Our phlogopite analyses in Table 2 also support this conclusion.

Mineralogy of an eclogite xenolith in a kimberlite dike near Ithaca

A small 1 cm³-size eclogite xenolith was found in a kimberlite dike of the Taughannock Creek near Ithaca. The eclogite consists of medium grained, anhedral grains of garnet and clinopyroxene in equal proportion. The analyses of 2 sets of coexisting garnet and clinopyroxene pair from two different portions of this eclogite are reported in Table 2. Kay et al. (1983) described two groups of clinopyroxenes from the Ithaca kimberlites. The first group has Cr₂O₃ content greater than 1% and Al₂O₃ content close to 3%. The second group of clinopyroxenes have Al₂O₃ contents in the range 4–6% and Na₂O contents near 2% and are found to be more common in these kimberlites. Our eclogitic clinopyroxene is similar in composition to this second group (Table 2). The almandine-rich garnet of this eclogite is similar in composition to eclogitic garnets from the Kao kimberlite pipe in southern Africa (MacGregor 1979). It is interesting to note that the discrete, more common garnets

Table 2. Electron microprobe data of the constituent minerals in the kimberlite dikes of New York State along with garnets and coexisting pyroxenes of two eclogite xenolith fragments (TF 567.2 and TF 567.3 found in the Taughannock dike near Ithaca)

	Dewitt Dike - D3			Manheim Dike - M3		Taughannock Creek Dike (5-1)			Euclid Avenue Dike	
	Unstrained phlogopite	Strained phlogopite	Perovskite	Unstrained phlogopite	Strained phlogopite	Unstrained olivine	Strained olivine	Euhedral olivine	Unstrained olivine	Groundmass olivine
SiO ₂	39.76	39.14	0.11	40.02	39.55	40.97	41.28	40.46	40.40	40.38
TiO ₂	2.06	2.25	52.54	2.02	1.93	0.00	0.00	0.00	0.00	0.01
Al ₂ O ₃	12.47	12.59	2.72	13.62	13.51	0.00	0.00	0.04	0.00	0.00
Cr ₂ O ₃	0.00	0.00	0.20	0.00	0.00	0.03	0.00	0.07	0.00	0.00
FeO	6.51	6.40	1.50	9.09	8.96	10.69	12.18	9.05	9.54	9.75
MnO	0.09	0.09	0.00	0.04	0.04	0.10	0.13	0.11	0.08	0.12
MgO	26.04	25.53	0.07	22.86	22.82	47.41	46.70	48.13	47.84	14.57
CaO	0.07	0.05	34.82	0.00	0.31	0.16	0.14	0.28	0.11	0.14
Na ₂ O	0.04	0.05	0.02	0.08	0.10	0.00	0.00	0.00	0.00	0.00
K ₂ O	9.79	9.86	0.14	9.36	9.54	0.05	0.06	0.09	0.03	0.05
Total	96.84	95.96	92.09	97.09	96.77	99.43	100.47	98.23	97.99	98.02
	0=22	0=22	0=3	0=22	0=22	0=4	0=4	0=4	0=4	0=4
Si	5.627	5.597	0.002	5.678	5.646	1.014	1.012	1.010	1.007	1.008
Ti	0.216	0.239	0.962	0.212	0.205	0.000	0.000	0.000	0.000	0.000
Al	2.081	2.119	0.078	2.277	2.271	0.000	0.000	0.000	0.001	0.000
Cr	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe	0.768	0.764	0.030	1.078	1.068	0.250	0.220	0.230	0.198	0.203
Mn	0.008	0.008	0.000	0.004	0.004	0.002	0.001	0.001	0.001	0.002
Mg	5.495	5.442	0.002	4.833	4.857	1.711	1.747	1.770	1.778	1.771
Ca	0.008	0.004	0.909	0.000	0.046	0.002	0.003	0.002	0.002	0.003
Na	0.008	0.012	0.000	0.021	0.025	0.000	0.000	0.000	0.000	0.000
K	1.765	1.796	0.003	1.694	1.735	0.001	0.001	0.001	0.000	0.001
Total	15.977	15.980	1.989	15.795	15.857	2.980	2.985	2.984	2.988	2.988
Mg/(Mg+Fe)						0.8763	0.8882	0.8850	0.8998	0.8972

found in the Cornell Campus dike (Table 2) are chrome-pyropes which are usually associated with garnet peridotite xenoliths in kimberlites. MacGregor and Carter (1970) further noted two groups of eclogite xenoliths on the basis of chemistry – Type I, (cumulate type) and Type II which are considered fractional crystallization products. On the basis of the CaO content of the garnet and the Na₂O content of the coexisting clinopyroxene, the eclogite xenolith under consideration belongs to Type II of the above classification.

Banno (1970) defined the garnet-clinopyroxene distribution coefficient $K_D = (\text{Fe}^{2+}/\text{Mg})_{\text{garnet}} / (\text{Fe}^{2+}/\text{Mg})_{\text{clinopyroxene}}$ and showed the temperature dependence of K_D , which has been proven to be a useful geothermometer for the bimimetic rock, eclogite. The temperature dependence of this K_D was further calibrated, from thermochemical and experimental data by Ganguly (1979), who proposed the equation

$$T^\circ(K) = \frac{4100 + 11.07P + 1586X_{\text{Ca}}^{\text{gt}}}{\ln K_D + 2.4}$$

where $T^\circ(K)$ is the temperature of equilibration, $X_{\text{Ca}}^{\text{gt}}$ is the mole fraction of Ca in garnet and P is the pressure in kilobars. For the data in Table 2, we obtain $T = 960^\circ\text{C}$ and 920°C for the two eclogites, assuming a pressure of 25 kbars. Under a normal continental geothermal gradient, this temperature of 960°C may be encountered at depths of 150 km – a reasonable depth of origin for this eclogite.

Sm – Nd systematics of kimberlites of New York

The kimberlites chosen for this study are fine-grained, bluish gray and consist mostly of a carbonate-silicate mixture. They also contain variable amounts of small phenocrysts of olivine and phlogopite set in a fine-grained matrix of serpentine, calcite, phlogopite, perovskite and magnetite-rich spinel.

Table 3 shows the Sm and Nd contents and ¹⁴⁷Sm/¹⁴⁴Nd and ¹⁴³Nd/¹⁴⁴Nd ratios of nine kimberlite dikes from New York State. Three other kimberlites from Missouri and Kentucky and one nepheline syenite from Virginia were also analyzed. The analytical methods for determining the Sm – Nd systematics as reported in Table 3 are similar to those described by Nakamura et al. (1976). The reported ¹⁴³Nd/¹⁴⁴Nd ratios were normalized to a ¹⁴⁶Nd/¹⁴⁴Nd ratio of 0.7219, and the procedural blanks were of the order of 80 and 250 picograms for Sm and Nd, respectively. Errors in the estimation of Sm and Nd contents are 0.1% or less.

Fractionated light rare-earth patterns, with respect to chondrites, are implied by the concentration data of the kimberlites in Table 3. These concentration data and the Sm/Nd ratio of the New York kimberlites are comparable to those of the kimberlites from the Kimberley area in South Africa (Basu and Tatsumoto 1980). The isotopic compositions of Nd are similar in most of the New York

Table 2 (continued)

	TF 567.2 (Eclogite inclusion)		(Cornell Dike Garnets)			TFA (Carbonatite)		(Taughannock Creek Dike 2-2)		TF 567.3 (Eclogite inclusion)		
	Garnet	Clinopyroxene	Garnet 1	Garnet 2 (core)	Garnet 3 (rim)	Unstrained phlogopite (core)	Unstrained phlogopite (rim)	Unstrained olivine	Strained olivine	Garnet	Clinopyroxene (core)	Clinopyroxene (rim)
SiO ₂	39.80	50.88	41.68	42.22	41.77	36.77	36.98	36.91	40.84	38.98	51.07	52.05
TiO ₂	0.00	0.16	0.01	0.02	0.00	3.05	2.98	0.01	0.00	0.00	0.20	0.21
Al ₂ O ₃	22.91	6.15	22.68	22.57	23.59	16.14	16.61	0.00	0.00	22.22	6.34	4.88
Cr ₂ O ₃	0.02	0.00	1.99	2.16	1.65	0.81	0.39	0.00	0.00	0.00	0.00	0.00
FeO	22.77	7.82	9.13	9.21	9.36	6.06	6.54	9.16	10.64	22.78	8.32	6.11
MnO	0.38	0.14	0.32	0.32	0.36	0.05	0.11	0.11	0.13	0.42	0.11	0.09
MgO	11.93	13.95	21.75	21.61	21.97	23.19	22.86	47.46	48.38	11.61	13.98	15.14
CaO	5.73	20.09	5.07	5.04	4.84	0.00	0.04	0.13	0.11	5.95	20.16	21.18
Na ₂ O	0.00	1.57	0.00	0.00	0.00	0.22	0.28	0.00	0.00	0.00	1.42	1.28
K ₂ O	0.07	0.05	0.04	0.03	0.05	9.80	10.05	0.07	0.06	0.08	0.07	0.04
Total	103.62	100.80	102.66	103.21	103.61	96.09	96.83	96.85	100.16	102.05	101.67	100.99
	0=12	0=6	0=12	0=12	0=12	0=22	0=22	0=4	0=4	0=12	0=6	0=6
Si	2.920	1.868	2.912	2.936	2.891	5.259	5.259	1.007	1.011	2.915	1.861	1.895
Ti	0.000	0.004	0.000	0.000	0.000	0.327	0.317	0.000	0.000	0.000	0.005	0.005
Al	1.981	0.265	1.868	1.849	1.923	2.720	2.784	0.000	0.000	1.958	0.271	0.208
Cr	0.000	0.000	0.108	0.118	0.089	0.088	0.042	0.000	0.000	0.000	0.000	0.000
Fe	1.397	0.239	0.533	0.534	0.540	0.722	0.776	0.192	0.220	1.425	0.253	0.186
Mn	0.023	0.003	0.108	0.020	0.020	0.004	0.012	0.002	0.002	0.026	0.003	0.002
Mg	1.305	0.764	2.266	2.238	2.267	4.945	4.846	1.785	1.747	1.293	0.759	0.821
Ca	0.450	0.790	0.379	0.375	0.359	0.000	0.004	0.003	0.002	0.476	0.787	0.826
Na	0.000	0.111	0.000	0.000	0.000	0.059	0.0	0.000	0.000	0.000	0.099	0.089
K	0.006	0.002	0.002	0.002	0.004	1.788	1.824	0.002	0.001	0.006	0.003	0.001
Total	8.083	4.044	8.085	8.072	8.094	15.911	15.937	2.991	2.994	8.099	4.042	4.032
Mg/(Mg+Fe)	0.4830	0.4406	0.8113	0.8074	0.8076			0.9029	0.8882	0.4757		
Ca/(Ca+Mg+Fe)										0.4375	0.4506	

Table 3. Sm, Nd contents and the isotopic composition of Nd in New York kimberlite dikes, in the Virginia nepheline syenite dike, and in kimberlites from Avon, Missouri, and Elliot County, Kentucky

Kimberlite	Sm (ppm)	Nd (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd
Loc 10 Williams Brook, near Ithaca	6.912	49.711	0.0839	0.51275±2
C-1 Clintonville Dike, near Syracuse	12.590	125.742	0.0605	0.51265±2
E-1 Euclid Avenue Dike, Syracuse	9.082	67.258	0.0815	0.51268±2
Frontenack Creek Dike, near Ithaca	16.843	124.111	0.0819	0.51272±3
TF3A Taughannock Falls Dike, near Ithaca	9.533	68.437	0.0842	0.51268±3
D4B DeWitt Dike, Syracuse	9.322	63.972	0.0880	0.51274±3
Portland Point Dike, near Ithaca	12.032	84.451	0.0861	0.51275±2
Manheim Dike, near Ithaca	8.266	51.404	0.0972	0.51271±2
Ithaca (Cascadilla) Kimberlite Dike	10.725	72.816	0.0890	0.51260±2
VA Virginia Nepheline Syenite Dike	8.721	71.622	0.0736	0.51264±2
Elliot County, Eastern Kentucky Kimberlite	15.617	117.065	0.0806	0.51270±4
48W-254 (Avon), Missouri Diatreme	7.464	45.308	0.0995	0.51253±3
48W-168-46' (Avon), Missouri Diatreme	7.633	61.289	0.0752	0.51251±3

dikes and are comparable to those of the nepheline syenite from Virginia and of the kimberlite from eastern Kentucky. The 2 Avon kimberlite samples have lower ¹⁴³Nd/¹⁴⁴Nd ratios than the other kimberlites of Table 3. This is because this diatreme is considerably older than the New York dikes

(Zartman et al. 1967). We have previously reported (Basu and Tatsumoto 1980) one analysis of the diatreme in Avon. Here we report two more analyses of the Avon dike rock 3,000 m. ESE of the main diatreme and from depths of 14 m and 76 m, respectively. The new Sm-Nd analyses

Table 4. K-Ar age determinations, including Na₂O and K₂O contents of New York kimberlites, Elliot County kimberlites, and of the nepheline syenite dike from Virginia

Kimberlite	Na ₂ O%	K ₂ O%	⁴⁰ Ar (10 ⁻¹⁰ moles/gm)	% ⁴⁰ Ar	Age (m.y.) ± 2σ
Loc 10 Williams Brook, near Ithaca	0.10	1.73	3.600	78.8	139 ± 7
C-1 Clintonville Dike, near Syracuse	0.13	1.10	2.044	32.0	125 ± 13
E-1 Euclid Avenue Dike, Syracuse	0.09	1.20	2.288	31.8	128 ± 10
Fronteneck Creek Dike, near Ithaca	0.09	0.49	1.027	64.6	140 ± 8
TF3A Taughannock Falls Dike, near Ithaca	0.15	1.05	1.877	57.7	121 ± 23
D4B DeWitt Dike, Syracuse	0.12	3.13	6.085	87.1	130 ± 13
Portland Point Dike, near Ithaca	0.48	0.61	1.022	64.2	113 ± 11
Manheim Dike, near Ithaca	0.10	2.14	5.687	80.9	176 ± 17
Ithaca (Cascadilla) Kimberlite Dike	0.10	1.60	3.491	84.8	146 ± 8
VA Virginia Nepheline Syenite Dike	9.30	5.51	9.136	89.4	112 ± 11
Elliot County, Eastern Kentucky Kimberlite	0.25	1.05	1.241	36.0	80 ± 6

of these dike rocks are very similar to the analysis of the main diatreme rock reported earlier.

Potassium-argon age determination

Eleven kimberlite samples, mostly from the central New York area, were analyzed for age determination by the potassium-argon method. The crushed kimberlite samples were split into two portions – one for Sm–Nd analysis, the other for Na₂O, K₂O, and K–Ar determinations. The results of the K–Ar age determination are shown in Table 4. The New York dikes give a range of age from 113 Ma to 176 Ma, with the majority of the dikes clustering around 140 Ma – an age that Zartman et al. (1967) concluded from Rb–Sr analyses to be the true age of the New York kimberlites. Zartman et al. (1967) also cautioned against using K–Ar ages of phlogopites from these kimberlites as representative of true age of emplacement. This is because many of their analyses of phlogopites in New York kimberlites yielded K–Ar ages greater than can be inferred from stratigraphic relationships, which suggests that either these phlogopites are xenocrysts in kimberlites or that they have formed with excess radiogenic argon.

We were careful in selecting our sample, particularly in view of the extremely heterogeneous xenocryst and phenocryst content of kimberlites. Our analyzed samples had only a few phenocrysts or xenocrysts and most of the micas were in the groundmass, embedded in the calcite matrix. In spite of our care in selecting these samples, we obtained a range of 113 to 176 Ma for the New York kimberlites. Two of the most fresh, xenocryst-free samples which were analyzed are the Loc 10 Williams Brook kimberlite and the kimberlite from the Cornell University (Ithaca) campus (Table 4). These two samples provide, within errors, identical ages of 139 ± 7 Ma and 146 ± 8 Ma, respectively. Therefore, we have chosen 143 Ma as the age of emplacement of the New York dikes, in agreement with the conclusion of Zartman et al. (1967).

The nepheline syenite dike of Staunton, Virginia, yields an age of 112 ± 11 Ma, similar to a Rb–Sr age of 114 ± 12 reported by Zartman et al. (1967). However, our K–Ar data (Table 4) of the Elliot County kimberlite from Kentucky yields an age of 80 ± 6 Ma, considerably lower than the concordant Rb–Sr and K–Ar early Permian age (270 Ma) reported by Zartman et al. (1967) from xenocrystic mica in this kimberlite. We prefer a 80 Ma age for the

Elliot County kimberlite, because, in addition to our K–Ar data on this rock, the initial Nd isotopic composition of this kimberlite based on an 80 Ma age is comparable to those of the Mesozoic kimberlites of eastern United States and southern Africa.

Nd isotopes in kimberlite and mantle evolution

Our knowledge of the history and evolution of the earth's mantle has increased considerably with the application of the Sm–Nd method in the study of mantle-derived rocks. The fact that the initial ¹⁴³Nd/¹⁴⁴Nd ratios of many young and old rocks which were supposedly derived from the mantle fit the chondritic growth curve suggests that a portion of the earth's mantle has an average Sm/Nd ratio close to that of chondrites. The deviations of the initial ¹⁴³Nd/¹⁴⁴Nd ratios of mantle-derived rocks from the chondritic bulk-earth growth curve is conventionally indicated by the notation ϵ_{Nd} . The ϵ_{Nd} value of zero or near zero in mantle-derived samples indicates undifferentiated mantle source in terms of Sm/Nd ratios. Positive or negative departures from the ϵ_{Nd} value of zero indicate at least one episode of fractionation from the chondritic ratio. We will discuss the Nd-isotopic compositions of the kimberlites of the present study in terms of this parameter ϵ_{Nd} . In calculating these ϵ_{Nd} values, we have used the following bulk earth chondritic parameters: ¹⁴⁷Sm/¹⁴⁴Nd = 0.1967 and the present-day ¹⁴³Nd/¹⁴⁴Nd = 0.512636 as suggested by Jacobsen and Wasserburg (1980). The kimberlites' ϵ_{Nd} values can then be compared with the large number of Nd-isotopic ratio measurements of volcanic rocks which were obtained in the past 6 years. The most important characteristics of these data are (DePaolo 1981): (i) almost all oceanic basalts have ϵ_{Nd} between +4 to +12, (ii) continental flood basalts have distinctly different ϵ_{Nd} values (-4 to +4) from the oceanic basalts, and (iii) the calc-alkaline rocks of island arcs show an ϵ_{Nd} value of +6 to +10, very similar to ocean-island basalts. There are several exceptions, however, to these above generalities. For example, several ocean island basalts including Tristan de Cunha, Gough and Kerguelen show ϵ_{Nd} less than +4, similar to continental flood basalts.

Before we discuss the Nd-isotopic data of the kimberlites, it is essential to describe the two-layer mantle model that has been proposed recently by Wasserburg and DePaolo (1979), and which is based on the aforementioned data. According to this model, the lower mantle is undiffer-

entiated with respect to Sm, Nd, and other lithophile elements and has retained an ϵ_{Nd} value of zero since the formation of the earth. Further, this lower mantle is overlain by the upper mantle which is depleted in Nd relative to Sm and has a positive ϵ_{Nd} value of +12. The positive ϵ_{Nd} value is considered, in this model, to be the result of ocean-floor formation at ridges and of subduction beneath trenches. In constructing this model, Wasserburg and De-Paolo (1979) were apparently impressed by the rather limited data on continental flood basalts which seemed to cluster at $\epsilon_{\text{Nd}}=0$, the value characteristic of undifferentiated mantle. However, Carlson et al. (1981) recently showed a wide variation in the ϵ_{Nd} values of the Columbia River flood basalts of -10.8 to +7.8, which is suggestive of mixing processes acting after the formation of the primary magma from the mantle source. Although the results of the study by Carlson et al. (1981) do not exclude the existence of primordial mantle, these data indicate the possibility of continental crustal-contamination of the basaltic magmas derived from depleted mantle.

ϵ_{Nd} in New York kimberlites

The ϵ_{Nd} values of the New York kimberlites are shown in Table 5 along with their K-Ar age of emplacement. The ϵ_{Nd} values range from +1.2 to +4.2. The maximum variation are shown by the Williams Brook and Portland Point dikes (+4.2) and the Cornell campus dike (+1.2), which are similar in age of emplacement and are closely associated in space (Fig. 1). Although these two dikes are essentially identical in their mineralogy, the difference in the Nd-isotopic composition between the dikes must imply either some heterogeneity of the source regions in the mantle, or some contamination of the ascending kimberlitic liquid while still in the mantle by depleted mantle material.

Figure 3 is a histogram of the ϵ_{Nd} values for the kimberlites. A striking aspect of Fig. 3 is that the New York kimberlites show a conspicuously narrow range in the ϵ_{Nd} values, which does not overlap with any of the other known groups of volcanic rocks. It is remarkable that the Elliot County kimberlite from Kentucky and the Nepheline Syenite from Virginia show ϵ_{Nd} values of +2.5 and +1.9, well within the range of ϵ_{Nd} values of the New York kimberlites.

ϵ_{Nd} in southern African kimberlites

Table 6 and Fig. 3 show the ϵ_{Nd} values of the 90 Ma old kimberlites from southern Africa. Three of these analyses were reported earlier by Basu and Tatsumoto (1980). The ϵ_{Nd} values of the seven kimberlites show a narrow range from +0.8 to +2.1. In calculating the initial ratios of Nd, we have assumed that all these kimberlite diatremes were emplaced around 90 Ma, as indicated by Davis' (1978) U-Pb study on zircons from kimberlites.

Kramers et al. (1981) recently reported the Sr and Nd isotopic compositions of five southern African kimberlites, including three from Bultfontein, Wesselton and the De Beers pipe. The ϵ_{Nd} values from these kimberlites are reported by these authors to be in the range +3 to +5, about 2 epsilon units higher than our values. This small discrepancy, however, could be due to interlaboratory bias.

Basu and Tatsumoto (1980) found that the garnet lherzolite inclusions in the South African kimberlites showed both time-averaged Nd enrichment and depletion with re-

Table 5. Table showing ϵ_{Nd} and K-Ar ages of New York dikes. The nepheline syenite from Virginia and the eastern Kentucky kimberlite

New York kimberlitic dikes	K-Ar age in million years	$\epsilon_{\text{Nd}}^{\text{l}}$
Euclid Avenue Dike, Syracuse	128	+2.7 ± 0.4
DeWitt Dike, Syracuse	130	+3.9 ± 0.4
Williams Brook Dike, near Ithaca	139	+4.1 ± 0.4
Ithaca (Cascadilla Dike)	146	+1.2 ± 0.4
Clintonville Dike, near Syracuse	125	+2.3 ± 0.4
Manheim Dike, near Ithaca	176	+3.7 ± 0.4
Portland Point Dike, near Ithaca	113	+3.9 ± 0.4
Fronteneck Creek Dike, near Ithaca	140	+3.5 ± 0.4
Taughannock Falls Dike, near Ithaca	120	+2.5 ± 0.4
<i>Eastern Kentucky Kimberlite</i>		
Elliot County Kimberlite	80	+2.5 ± 0.4
<i>Virginia</i>		
Nepheline Syenite	112	+1.9 ± 0.4

Table 6. Table showing ϵ_{Nd} of Pre-Cretaceous kimberlite pipes from different continents. Sources of data: this study and Basu and Tatsumoto (1980). This table also includes the ϵ_{Nd} of some of the 90 Ma old kimberlites from southern Africa

Pre-Cretaceous Kimberlite Pipes	Age in million years	$\epsilon_{\text{Nd}}^{\text{l}}$
<i>South Africa</i>		
Premier	1300	0.0 ± 0.6
<i>Southern India</i>		
L-1 (Lattavaram)	940	+0.6 ± 0.5
L-2 (Lattavaram)	940	+0.2 ± 0.5
<i>United States</i>		
77-1 Avon Diatreme, Missouri	390	+1.2 ± 0.6
48-W-254 Avon Dike, Missouri	390	+1.8 ± 0.6
48-W-168 Avon Dike, Missouri	390	+2.7 ± 0.6
Nix 2, Colorado-Wyoming Pipe	377	+1.2 ± 0.6
<i>U.S.S.R.</i>		
Obnazennaya, Yakutia	150 (?)	+3.2 ± 0.8
<i>China</i>		
A _{III} Shandong Province	400 (?)	-0.5 ± 0.4
B _I Shandong Province	400 (?)	-0.5 ± 0.4
<i>Cretaceous Kimberlite Pipes</i>		
<i>Southern Africa</i>		
Bultfontein	90	+1.6 ± 0.8
Benfontein	90	+1.0 ± 0.5
De Beers (720 m level)	90	+1.1 ± 0.5
Wesselton	90	+1.2 ± 0.5
Pipe 200, Lesotho	90	+2.1 ± 0.5
Frank Smith	90	+0.8 ± 0.4
Newlands	90	+0.9 ± 0.4

spect to Sm. These authors also concluded that all inclusions, mafic and ultramafic, were unrelated to their kimberlite host. Although the kimberlites are characterized by light rare earth element enrichment, the ϵ_{Nd} values of the kimberlites indicate that the source regions of the kimberlites could

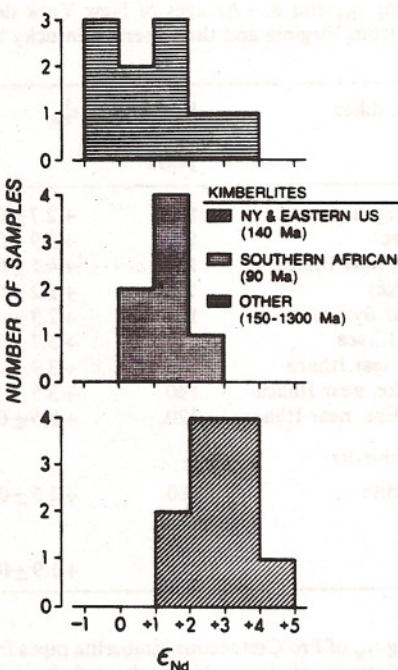


Fig. 3. Histogram plots of the ϵ_{Nd} values of the 140 Ma old New York kimberlites, of the 90 Ma southern African kimberlites and of the kimberlites which range in age from 150–1,300 Ma from south Africa, India, U.S.A., U.S.S.R. and China. Sources of data are this study and Basu and Tatsumoto (1980).

not have had a pattern of light rare earth element enrichment for a long period of time.

ϵ_{Nd} in Pre-Cretaceous kimberlites

The data for Pre-Cretaceous kimberlites from other parts of the world are shown in Table 6 and Fig. 3, which includes some analyses of kimberlites already reported by Basu and Tatsumoto (1980). The new analyses in Table 6 and in Fig. 3 include two kimberlite dike samples from Avon, Missouri, and two kimberlite pipe samples from the Shandong Province of the eastern part of China (Zhang et al. 1980). The age of these kimberlites range from 150 Ma to 1,300 Ma. The ages of the southern Indian kimberlites were reported earlier (Basu and Tatsumoto 1979). The Premier kimberlite is accepted to be 1,300 Ma old (Allsopp and Kramers 1977). The kimberlites from the eastern part of China give K–Ar ages in the range 265 to 755 Ma, with the majority of the samples falling between 300–500 Ma. We have accepted a tentative age of 400 Ma for these two Chinese kimberlites. The ϵ_{Nd} values for these older kimberlites fall in the range –0.5 to +2.7, with the majority in the neighborhood of +1.5. The three samples from Avon, Missouri, show some differences in the initial Nd isotopic ratios which might be beyond analytical uncertainty.

Discussion

It is clear from Fig. 3 that the ϵ_{Nd} values of all kimberlites cluster in the range 0 to +4. Basu and Tatsumoto (1978, 1979, 1980) considered the initial ϵ_{Nd} values of kimberlites to be near zero and slightly positive. Subsequently, the chondritic bulk earth growth curve has been revised (Jacobsen and Wasserburg 1980), and if we use these new parame-

ters, the ϵ_{Nd} values of kimberlites reported earlier becomes slightly more positive. However, the most striking aspect of all the kimberlite data, as summarized in Fig. 3, is their unique and narrow range of ϵ_{Nd} values. Except for the continental flood basalts, no other major group of young volcanic rocks covers the range of ϵ_{Nd} values of the kimberlites. The continental flood basalts show a much greater range (Carlson et al. 1981), more than twice the range of ϵ_{Nd} values displayed by the kimberlites. Thus, the kimberlites are produced from an unique mantle reservoir beneath the continents, and this mantle reservoir appears to be relatively primitive. It also follows from this observation that the oceanic basalts are not entirely produced from a parent similar to the kimberlite's source in the mantle.

In a recent study, McCulloch et al. (1983) have reported Nd and Sr isotopes in kimberlites and associated lamproites from Western Australia. These rocks have isotopic compositions ($\epsilon_{\text{Nd}} = -7.4$ to -15.4 , $^{87}\text{Sr}/^{86}\text{Sr} = 0.7104$ to 0.7187) indicating their derivation from highly enriched mantle sources with high Nd/Sr and Rb/Sr ratios. On the basis of these data, these authors propose to explain the "mantle array" by a mixing model in which highly enriched mantle, similar to the Australian kimberlites, is mixed with depleted, MORB-type, mantle. According to these authors, the clustering of ϵ_{Nd} values near zero for other kimberlites (Basu and Tatsumoto 1978, 1980) can be modelled as blends of enriched and depleted mantle. Although we do not rule out this possibility, most of the kimberlite data (this study and Kramers et al. 1981), in our opinion, can be explained by assuming either an undepleted source or by contamination of an undepleted mantle ($\epsilon_{\text{Nd}} = 0$) by depleted mantle ($\epsilon_{\text{Nd}} = 10$). It is also possible that the unusual Nd and Sr isotopic compositions of the Western Australian kimberlites and lamproites reflect contamination of an undepleted mantle-derived liquid by liquids derived from an enriched mantle.

Anderson (1981) has recently outlined a scheme of mantle evolution in which he proposes that kimberlites represent the interstitial melt of a garnet-rich (eclogitic) layer below 220 km, which is the natural consequence of differentiation of the earth in a magma ocean. He further proposes that partial melting of this eclogitic layer produces picritic magmas and MORB. An undepleted eclogite layer, or cumulate, will, according to Anderson's model, give primitive ratios of Nd isotopes to any interstitial fluid, such as kimberlite. Tatsumoto (1978), based on Pb isotopes, had also previously suggested an evolutionary model for the mantle in which the earth was initially molten and convection within a continually cooling cell separated the inner, less depleted parts from the depleted outer parts. Finally, according to the model, the original cell will split and hot plumes may arise from the center of the cell.

The partial melting of dolomite- or magnesite-bearing phlogopite peridotite is generally considered to be a suitable source of kimberlite (e.g. Wyllie 1980). This melting is possibly due to the diapiric rise of a plume and due to the associated changes in the pressure-temperature conditions. Wyllie (1980) proposed a new diapiric model for kimberlite genesis which takes into account pressure- and temperature-induced melting relationships in a rising diapir of carbonated peridotitic mantle. The scenario presented by Wyllie may have considerable bearing in interpreting our Nd-isotopic data on kimberlites, and should be discussed here. According to his model, a thermal perturbation in the deep

mantle will cause release of vapors of C—H—O composition. These rising volatile components would induce partial melting and trigger the rise of adiabatic diapirs from 260 km depth, within the diamond stability field. In the rising diapirs, the percentage of liquid increases and finally the partially molten diapir crystallizes at 80 km depth where it reaches a temperature maximum. The release of volatiles from the diapir enhances crack propagation, which ultimately forms conduits to discharge magma to the surface.

An interesting aspect of this model, in connection with our observed Nd-isotope ratios in kimberlites, is that the CO₂ and H₂O in the kimberlites are originally derived from the deep volatile components C—H—O below 260 km depth. High concentrations in kimberlites of large-ion-lithophile elements, including the light rare earths are possibly the consequences for the fractionating and migratory nature of the volatile phases in kimberlites. Since these volatiles are transmitted through a large vertical section of at least the order of 150 km, there will be abundant opportunities for mixing of the isotopically heterogeneous layers of the mantle from different levels.

The Nd-isotopic data of kimberlites as presented in this study are still compatible with a layered, isotopically heterogeneous, mantle model in which the ultimate sources of the rare earth elements, which now show an ε_{Nd} value of near zero or slightly positive, are from a relatively undifferentiated and primitive chondritic source. Certainly, the Nd-isotopic signature of kimberlites is distinctive and is not characteristic of any other petrologically consanguineous suite of volcanic rocks. Finally, it should be pointed out that the occurrences of the kimberlites in the eastern part of North America have been correlated with Mesozoic hotspot epeirogeny (Crough 1981) and with the reactivation of the basement faults of the Appalachian plateau during the opening of the Atlantic ocean (Parrish and Lavin 1982). Although the southern African kimberlites are relatively young (90 Ma age) compared with the eastern United States dikes (140 Ma), the Nd isotopic signature of kimberlites from both the continents are compatible with a model of deep-seated diapirism originating from primitive layers within the mantle, which ultimately manifests itself into epeirogeny and continental drift.

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