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K-Ar AND Rb-Sr AGES OF SOME ALKALIC INTRUSIVE ROCKS FROM CENTRAL AND EASTERN UNITED STATES†

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ABSTRACT. Numerous small bodies of alkalic intrusive rocks ranging in composition from syenite to peridotite occur in the central and eastern United States. Attempts to date these intrusive rocks by long-range correlations with petrographically similar rocks of known age are generally unsatisfactory, and geologic relationships have only established the fact that they postdate their respective host rocks. K-Ar and Rb-Sr ages on biotite and hornblende from some of these intrusive rocks show that they represent several different periods of emplacement: (1) syenitic bodies which intrude Ordovician rocks near Beemerville, New Jersey, yield a Late Ordovician age of 435 ± 20 million years; (2) diatremes of mica peridotite which cut Cambrian rocks in southeastern Missouri give an Early to Middle Devonian age of 390 ± 20 million years; (3) dikes, sills, and explosion breccia in Mississippian carbonate rocks from the Rosiclare fluorite district of Illinois and Kentucky and kimberlite from Elliott County, Kentucky, have an Early Permian age of 265 ± 15 million years; (4) isolated mica peridotites, nepheline syenites, and alkalic lamprophyres in various areas of Paleozoic rocks give Jurassic to Cretaceous ages. Within this latter group, the intrusions along the western side of the metamorphic Appalachian Mountains in Vermont, New York, and Virginia have ages of approximately 120 to 150 million years, and the distinctly younger alkalic rocks of Magnet Cove and Little Rock, Arkansas, and Silver City and Rose domes, Kansas, have ages of 95 ± 8 million years.

Of special interest are phlogopite phenocrysts in peridotites from New York and Pennsylvania which yield K-Ar ages greater than can be inferred from stratigraphic relationships. This suggests that these micas may be xenocrysts either derived from older basement rocks or formed with excess radiogenic argon in their structure.

The strontium isotopic composition of apatites from several of these alkalic rocks is rather primitive with respect to many igneous rocks and has an average Sr^{87}/Sr^{86} ratio of 0.703.

Many of the intrusions that were dated lie in swarms along a structural lineament that follows the 38th parallel of latitude, from Kansas into West Virginia. The wide range in age of the intrusions along this line suggests that they overlie a fault deep in the Earth's crust, along which movements were renewed through Paleozoic and Mesozoic time. Igneous activity in the East continued for at least 50 million years past the commonly accepted termination date in Triassic time.

INTRODUCTION

A regional petrographic study of some alkalic intrusive rocks from central and eastern United States is currently being conducted by the U. S. Geological Survey. Interest in the numerous small bodies and localized dike swarms of syenitic to peridotitic rock which apparently constitute an alkalic igneous province since late Precambrian time in this area (Brock and Heyl, 1961) has recently been revived by the search for possible deep crustal and mantle derived rocks. Also, several of these intrusion clusters are found in close proximity to galena, sphalerite, barite,

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and fluorite deposits and, therefore, are possibly genetically related. During the course of the investigation, a rather extensive geochronologic program was undertaken to establish the age of emplacement of many of the intrusives. The results of these radiometric age determinations is the subject of the present paper. A more detailed mineralogical and textural description of these rocks will be forthcoming in a future paper by Brock, Heyl, Jolly, and Zartman (manuscript in preparation).

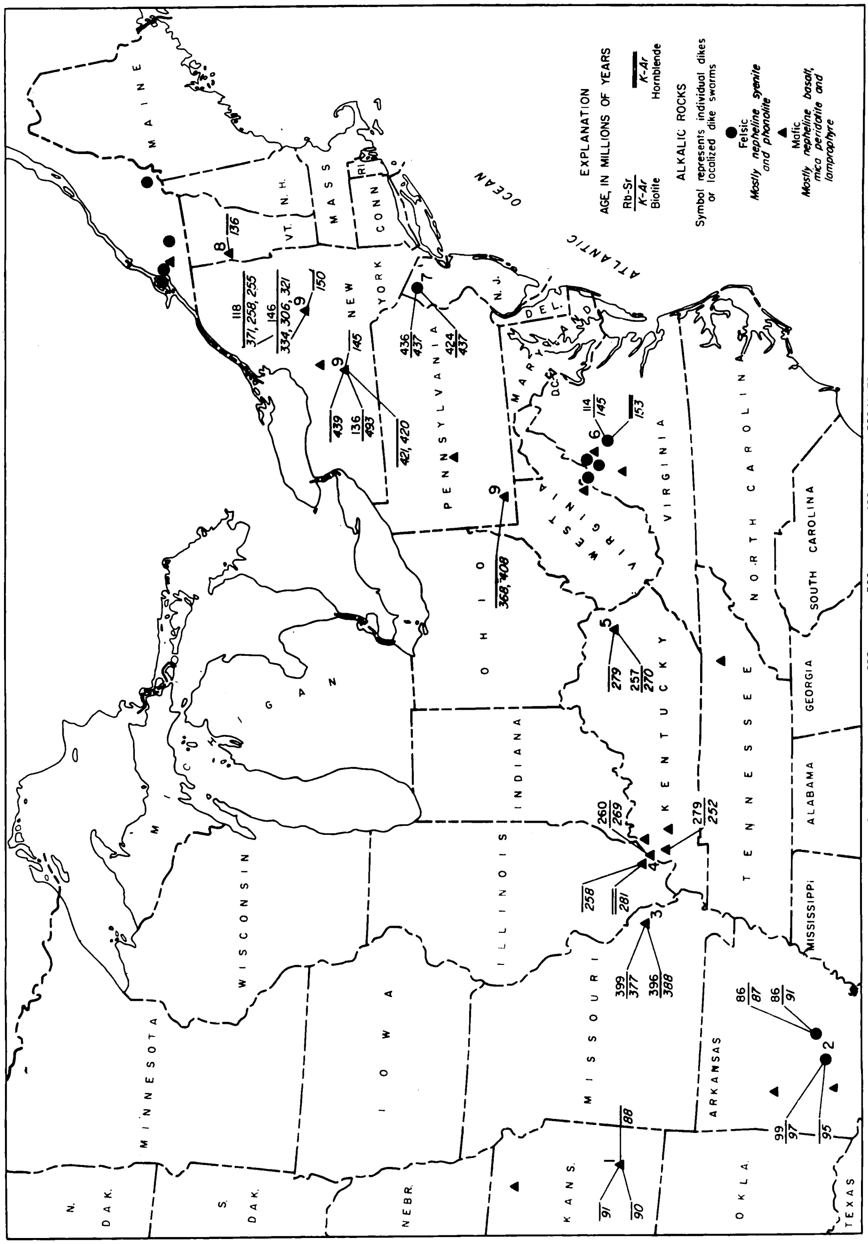
The rocks included in this study are but a portion of the great number of alkalic intrusions known within the craton of United States between the Appalachian Mountains and the Rocky Mountains (Brock and Heyl, 1961). They constitute a petrologic province in which stocks, plugs, sills, dikes, and diatremes of alkalic rocks form more than 90 percent of the exposed intrusions in this large part of the country. This occurrence contrasts with other parts of the continent in which there is a great preponderance of subalkalic rock types. Such subalkalic intrusions are notably absent here, and only the alkalic rocks are present in any important volume (fig. 1).

Alkalic peridotites and syenites in this region, as in other parts of the world, generally occupy deep-seated fractures and pipes that penetrate an essentially stable platform. Most of the intrusions are mafic, but they include a wide range of petrologic types from nepheline syenite to alkalic peridotite. Nearly all are partly carbonatized, and at Magnet Cove, Arkansas, carbonatites are recognized.

The mafic dikes and plugs characteristically have altered their enclosing wallrocks only slightly, and a few possess visible chilled margins. While some of them have solidified in place from a melt, most are of a texture indicating that little or no liquid magma phase was present at their exposed level. All have been emplaced in the highly fluid state, and the authors conclude, as many before them have, that the volatile content of the intrusion was high and that many were actually produced by a two-phase gas-solid mixture. Kimberlite, as the term is used in this paper, is an intrusive breccia with a matrix of either mica peridotite or its serpentinized or carbonatized derivatives. Field evidence supports emplacement of the kimberlite by explosion processes. One large mass of intrusive breccia, for example, was found to contain as its only recognizable igneous material isolated large (1 inch) xenocrysts of biotite. Such mica xenocrysts are common in most mica peridotite intrusions and in many lamprophyre dikes.

Preliminary optical and X-ray determinations have shown much of the mica included in this study to be phlogopitic. However, because complete chemical analyses are not available in most cases, all micas will simply be called biotites although a high Mg^{++}/Fe^{++} ratio is probably often present.

In the past many of the intrusions could only be shown to be younger than the sedimentary rock they intruded. A few in Arkansas (Miser and Ross, 1922) and in the Monteregian Hills in southern Quebec (Fairbairn and others, 1963) have been more precisely dated by either


EXPLANATION
AGE, IN MILLIONS OF YEARS
Rb-Sr / K-Ar Biotite
K-Ar Hornblende
ALKALIC ROCKS
Symbol represents individual dikes or localized dike swarms
Felsic
Mostly nepheline syenite and phonolite
Mafic
Mostly nepheline basalt, mica peridotite and lamprophyre
ATLANTIC OCEAN
MAINE
N. H.
VT.
MASS
R.I.
CONN
NEW YORK
PENNSYLVANIA
N. J.
DEL.
MARYLAND
D.C.
WEST VIRGINIA
VIRGINIA
NORTH CAROLINA
SOUTH CAROLINA
GEORGIA
ALABAMA
MISSISSIPPI
TENNESSEE
KENTUCKY
OHIO
INDIANA
ILLINOIS
MICHIGAN
WISCONSIN
MINNESOTA
IOWA
MISSOURI
ARKANSAS
OKLA.
TEXAS
KANS.
NEBR.
N. DAK.
S. DAK.
0
100
200
300
400
500 MILES

stratigraphic or radiometric methods as mid-Cretaceous and Jurassic to Cretaceous, respectively. Extrapolating from these Arkansas data, many geologists have assumed that most of these alkalic rocks are of a Mesozoic age (Kemp and Marsters, 1893; Honess and Graeber, 1926; Croneis and Billings, 1929; Tarr and Keller, 1933; Kidwell, 1947). Other authors, such as Tolman and Landes (1939), have pointed out that a wide range in ages is also possible. This present isotopic study was designed to define precisely the age of some of the main intrusions.

ACKNOWLEDGMENTS

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ANALYTICAL PROCEDURE

Mineral separation of mica and hornblende for age determination followed standard techniques with some modifications required by the high strontium environment in which these rocks formed (table 1). Those kimberlites containing xenocrysts of schist and gneiss were carefully processed, after crushing, to obtain mica from the matrix only. Hand picking of the desired material was employed whenever a coarse grain-size ($>$ 20 mesh) was available; in some samples, no additional processing was necessary. In other samples, including the mica of a smaller mesh size, mineral purification generally involved use of bromoform heavy liquids, a Frantz magnetic separator, and a mica shaker table. Because of the high strontium content of these alkaline rocks, it was mandatory to make every effort to free the mica from inclusions of apatite, carbonate, serpentine, et cetera. To this end grinding in alcohol, a technique similar to that described by Jäger (1962), was used in some cases to upgrade the final separate.

The experimental procedure for the K-Ar analyses is similar to that described previously (Goldich and others, 1961; Evernden and Curtis,

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Fig. 1. Post-Cambrian alkalic igneous rocks which intrude sedimentary rocks in parts of Central and Eastern United States. Radiometric ages for the dated samples are shown for the following localities: 1, Silver City and Rose domes, Kansas; 2, Little Rock and Magnet Cove, Arkansas; 3, Avon, Missouri; 4, Rosiclare, Illinois, and vicinity; 5, Elliott County, Kentucky; 6, Staunton, Virginia; 7, Beemerville, New Jersey; 8, Grand Isle, Vermont; 9, Pennsylvania-New York localities.

TABLE 1

Sample description and geologic setting of some alkalic intrusive rocks from Central and Eastern United States

Sample number	Lithology	Mineral analyzed and mesh-size		Geologic setting
Silver City and Rose domes, Kansas				
556	Mica peridotite	Biotite	−10 + 20	Hill Pond peridotite (Wagner, 1954) from Silver City dome, Fredonia quadrangle. Dike and sill structure intruding Upper Pennsylvanian sedimentary rocks; sample 556 from outcrop (in Hill Pond, NW1/4NE1/4sec. 32, T. 26 S., R. 15 E.); sample 557 from drill core (drill hole 21, depth 33.0 feet, located just west Hill Pond NE1/4NW1/4sec. 32, T. 26 S., R. 15 E.).
557	"	"	−40 + 80	
703	"	"	−80 + 120	Sample from drill core (drill hole 3, depth 54.6 feet, located 1866 feet north, 1240 feet west of SE corner sec. 13, T. 26 S., R. 15 E.), in Rose dome. Dikes intrude Upper Pennsylvanian sedimentary rocks.
Little Rock and Magnet Cove, Arkansas				
249	Nepheline syenite	Biotite	−20 + 40	Nepheline syenite stock from Granite Mountain near Little Rock. Intrudes upper Paleozoic sedimentary rocks and is overlain by Paleocene sedimentary rocks; samples from quarry exposures.
250	"	"	−20 + 40	
558	Melteigite	"	−10 + 20	Alkalic igneous complex at Magnet Cove (Erickson and Blade, 1963). Intrudes Mississippian sedimentary rocks; samples from outcrops.
562	Garnet ijolite	"	−40 + 80	
Avon, Missouri				
192	Kimberlite	Biotite	−10 + 20	Kimberlitic diatremes. Intrude Cambrian sedimentary rocks and also contain fossiliferous limestone xenoliths of Early and earliest Middle Devonian age; samples from outcrops. Sample 192 from Cash Farm (loc. 31 of Kidwell, 1947, p. 58); sample 194 from bed of Saline Creek (loc. 26 of Kidwell, 1947, p. 54).
194	"	"	−10 + 20	
Rosiclare, Illinois, and vicinity				
189	Kimberlite	Biotite	−10 + 20	Explosion breccia composed of silicified carbonate rock and phenocrystic biotite and hornblende from Hicks dome, Illinois. Structure involves Pennsylvanian and older rocks; sample from outcrop on Grant farm (center west line, NW1/4sec. 6, T. 12 S., R. 8 E.).
		Hornblende	−20 + 40	

197	Mica peridotite	Biotite	$-40 + 80$	Peridotite in subsurface at Levias, 5.5 miles west-southwest of Marion, Ky. Dike intrudes Mississippian sedimentary rocks; sample from drill hole (depth, 241 feet) on Adams property, southeast of U. S. Highway 60.
238	"	"	$-40 + 80$	Peridotite sill at Downey's Bluff, 0.5 mile south of the center of Rosiclare facing Ohio River. Intrudes Mississippian sedimentary rocks; sample from outcrop.
	Elliott County, Kentucky			
555	Kimberlite	Biotite (a)	$-10 + 20$	Kimberlitic diatremes from Ison Creek locality. Intrude Pennsylvanian sedimentary rocks; samples from two separate pieces of groundmass. Diatreme sampled is on north-facing hill, 0.5 mile south of Ison School, 8 miles southwest of Willard.
"		" (b)	$-20 + 40$	
	Staunton, Virginia			
563	Nepheline syenite	Biotite	$-40 + 80$	Nepheline syenite dike. Intrudes Ordovician sedimentary rocks; sample from roadcut on southeast side of highway at junction of old and new U. S. Route 11, 3 miles northeast of center of Staunton.
		Hornblende	$-40 + 80$	
	Beemerville, New Jersey			
260	Mafic syenite	Biotite	$-20 + 40$	Mafic syenite plug. Intrudes Upper Ordovician but not adjacent Silurian sedimentary rocks; sample from outcrop of plug on sharp oval hill locally known as Ruten's Hill, 1 mile west-northwest of Libertyville, Sussex County.
261	Nepheline syenite	"	$-40 + 80$	Nepheline syenite stock. Intrudes Upper Ordovician but not adjacent Silurian sedimentary rocks; sample from outcrop of central part of stock 1.5 mile north of center of Beemerville, on lower southeast slope of Kittatinny Mountain.
	Grand Isle, Vermont			
514	Lamprophyre	Biotite	$-40 + 80$	Lamprophyre dike from Lake Champlain swarm. Intrudes Ordovician sedimentary rocks; sample from outcrop, dike No. 7 of Shimer (1902) on west shore of Grand Isle, 1.5 miles west of South Hero.

TABLE 1 (continued)

Sample number	Lithology	Mineral analyzed and mesh-size	Geologic setting
	Masontown, Pennsylvania		
259	Kimberlite	Biotite −10 + 20	Kimberlitic diatreme exposed in coal mine. Intrudes Upper Pennsylvanian sedimentary rocks; sample from outcrop on northwest bank of Middle Run, 0.25 mile north of Adah, Fayette County.
	Portland Point, New York		
190	Kimberlite	Biotite (a) −10 + 20 " (b) −10 + 20 " (c) −10 + 20 " (d) −80 + 120	Kimberlitic dike about 8 miles north of Ithaca. Intrudes Middle Devonian sedimentary rocks; samples (a), (b), and (c) are definitely xenocrystic, while (d) from the fine-grained matrix of the rock may be either xenocrystic or authigenic. Dike is in east face Cayuga Crushed Stone Corporation quarry, 0.5 mile northeast of Portland Point.
	Manheim, New York		
193	Kimberlite	Biotite (a) −10 + 20 " (b) −10 + 20 " (c) −80 + 120	Peridotite dike near Little Falls, New York. Intrudes Lower Devonian sedimentary rocks; samples (a) and (b) are definitely xenocrystic in nature, while (c) from the fine-grained matrix of the rock may be either xenocrystic or authigenic. Samples from dike 3 (Smyth, 1896) at Power Plant on Canada Creek 0.25 mile north of East Creek.

1965). Direct fusion of the sample by an RF induction heater is used to extract the argon, and both dynamic and static mass spectrometry were used during this study. All potassiums were determined by flame photometry following the procedure of Shapiro and Brannock (1956). An accuracy of ± 5 percent has been assigned to all of the K-Ar ages in table 2.

The K^{40} decay constants used in calculating the potassium-argon ages are $\lambda_\beta = 4.72 \times 10^{-10}$ years^{-1} and $\lambda_\epsilon = 0.585 \times 10^{-10}$ years^{-1} (Aldrich and Wetherill, 1958). The natural abundance of K^{40} in atom percent is taken to be 0.119 percent (Nier, 1950a).

The chemical and isotope-dilution procedures for the Rb-Sr analyses are similar to those described by Zartman (1964). In addition to the isotope-dilution analyses, unspiked strontium compositions have been determined in duplicate for all the samples, and the average Sr^{87}/Sr^{86} ratios along with the other analytical results are given in table 3. The strontium data have been normalized to a Sr^{86}/Sr^{88} ratio of 0.1194. The uncertainty in the Rb^{87}/Sr^{86} ratio is approximately ± 2 percent of the ratio, and the normalized Sr^{87}/Sr^{86} ratio is known to ± 0.002. The error assigned to the age represents the most unfavorable conjunction of parent and daughter isotope uncertainties.

Rubidium-strontium ages have been calculated using a decay constant for Rb^{87} of 1.47×10^{-11} year^{-1} (Flynn and Glendenin, 1959). This is 6 percent greater than the decay constant of 1.39×10^{-11} years^{-1} proposed by Aldrich and Wetherill (1958). All the Rb-Sr ages would uniformly become 6 percent larger if the smaller decay constant were used. The natural abundance of Rb^{87} in atom percent is taken to be 27.85 percent (Nier, 1950b).

Strontium from the apatite in several of the alkaline rocks has been analyzed, and the resultant isotopic ratios are used to correct for initial strontium in calculating the ages. A discussion of the initial strontium isotopic composition and its bearing on the genesis of these alkalic rocks is given in the subsequent section.

INITIAL STRONTIUM ISOTOPIC COMPOSITION

Because the micas analyzed in this study contained high concentrations of initial or "common" strontium and, therefore, low radiogenic enrichments, it was necessary to obtain information on the isotopic composition of this initial strontium in order to reduce age uncertainties. Therefore apatite concentrates were obtained from several of the alkaline rocks, and their Sr^{87}/Sr^{86} ratios were determined (table 4). Where cogenetic apatite-biotite pairs were analyzed, the Sr^{87}/Sr^{86} ratio of the apatite is used for the isotopic composition of the initial strontium in calculating the age. Care was exercised to remove all carbonate material from the apatites because of the possibility that it was derived from intruded limestones rather than being a primary constituent of the igneous rock. The Rb/Sr ratios of the apatites were determined only by X-ray fluorescence, because their extremely low values indicated that no cor-

TABLE 2

Potassium-argon ages of some alkalic rocks from the Central and Eastern Interior Provinces (Sample number: B, Biotite; H, Hornblende)

Sample number	K_2O, %	Ar^{40*}, ppm	Ar^{40*}/K^{40}	Percent radiogenic	Age, m.y.
	Silver City and Rose domes, Kansas				
556B	8.06	0.0446	0.00546	97	91 ± 5
557B	8.52	0.0464	0.00538	95	90 ± 5
703B	7.85	0.0417	0.00527	83	88 ± 4
	Little Rock and Magnet Cove, Arkansas				
249B	9.03	0.0475	0.00519	90	87 ± 4
250B	8.81	0.0489	0.00548	90	91 ± 5
558B	9.91	0.0571	0.00569	91	95 ± 5
562B	9.08	0.0536	0.00583	95	97 ± 5
	Avon, Missouri				
192B	9.19	0.227	0.0244	95	377 ± 19
194B	8.66	0.221	0.0252	96	388 ± 19
	Rosiclare, Illinois, and vicinity				
189B	8.87	0.146	0.0162	96	258 ± 13
189H	2.12	0.0381	0.0177	97	281 ± 14
197B	8.70	0.139	0.0158	94	252 ± 13
238B	8.71	0.149	0.0169	97	269 ± 13
	Elliott County, Kentucky				
555B (a)	6.72	0.120	0.0176	94	279 ± 14
555B (b)	5.35	0.0919	0.0170	89	270 ± 14
	Staunton, Virginia				
563B	7.60	0.0676	0.00879	91	145 ± 7
563H	2.26	0.0213	0.00934	95	153 ± 8
	Beemerville, New Jersey				
260B	8.82	0.257	0.0288	98	437 ± 22
261B	9.19	0.268	0.0288	98	437 ± 22
	Grand Isle, Vermont				
514B	7.94	0.0662	0.00823	92	136 ± 7
	Masontown, Pennsylvania				
259B	9.84	0.237	0.0238	97	368 ± 18
		0.265	0.0266	86	408 ± 20
	Portland Point, New York				
190B (a)	9.02	0.264	0.0289	95	439 ± 22
190B (b)	10.05	0.336	0.0330	94	493 ± 25
190B (c)	9.65	0.269	0.0276	96	421 ± 21
		0.268	0.0275	96	420 ± 21
190B (d)	7.32	0.0652	0.00881	96	145 ± 7
	Manheim, New York				
193B (a)	8.58	0.208	0.0239	93	371 ± 19
		0.141	0.0162	96	258 ± 13
		0.139	0.0160	91	255 ± 13
193B (b)	9.64	0.208	0.0214	96	334 ± 17
		0.189	0.0194	95	306 ± 15
		0.199	0.0205	93	321 ± 16
193B (c)	7.08	0.0655	0.00914	94	150 ± 8

rection was necessary for radioactive decay subsequent to crystallization. For those samples in which no cogenetic apatite was analyzed, an average Sr^{87}/Sr^{86} ratio of 0.703 has been assumed.

Although apatites from a variety of alkalic rock types, including mica peridotite, nepheline syenite, and lamprophyre, were analyzed, a rather narrow range (0.7019-0.7041) in the initial Sr^{87}/Sr^{86} ratio was observed.

TABLE 3

Rubidium-strontium ages of some alkalic rocks from the Central and Eastern. Interior Provinces (Sample number: B, biotite)

Sample number	Rb, ppm	Sr, ppm	Sr^{87}/Sr^{86}	Sr^{87*}, ppm	Percent radiogenic	Age, m.y.
	Silver City and Rose domes, Kansas					
556B	230[a]	1200[a]	....	....	....	....
557B	190[a]	760[a]	....	....	....	....
703B	170[a]	580[a]	....	....	....	....
	Little Rock and Magnet Cove, Arkansas					
249B	468	15.3	0.8157	0.167	13.82[b]	86 ± 3
250B	476	14.0	0.8276	0.171	15.06[b]	86 ± 3
558B	330[a]	480[a]	....	....	....	....
562B	386	48.8	0.7365	0.160	4.55[b]	99 ± 8
	Avon, Missouri					
192B	334	109	0.7552	0.557	6.91[b]	399 ± 23
194B	375	156	0.7434	0.621	5.43[b]	396 ± 28
	Rosiclare, Illinois, and vicinity					
189B	290[a]	350[a]	....	....	....	....
197B	426	193	0.7293	0.497	3.61[c]	279 ± 27
238B	448	164	0.7320	0.484	4.11[d]	260 ± 23
	Elliott County, Kentucky					
555B (b)	443	156	0.7342	0.475	4.25[b]	257 ± 22
	Staunton, Virginia					
563B	495	97.5	0.7277	0.235	3.37[e]	114 ± 12
	Beemerville, New Jersey					
260B	289	201	0.7298	0.527	3.67[b]	436 ± 41
261B	801	194	0.7783	1.421	9.67[b]	424 ± 20
	Masontown, Pennsylvania					
259B	450[a]	640[a]	....	....	....	....
	Portland Point, New York					
190B (b)	551	65.6	0.7516	0.312	6.47[b]	136 ± 8
	Manheim, New York					
193B (a)	392	105	0.7219	0.194	2.62[b]	118 ± 15
193B (b)	464	55.6	0.7548	0.282	6.86[b]	146 ± 8

[a] Rubidium and strontium concentrations by X-ray fluorescence only; not analyzed isotopically because of unfavorable Rb/Sr ratio.
[b] Initial Sr^{87}/Sr^{86} ratio assumed to be 0.703.
[c] Initial Sr^{87}/Sr^{86} ratio from coexisting apatite determined to be 0.7030.
[d] Initial Sr^{87}/Sr^{86} ratio from coexisting apatite determined to be 0.7019.
[e] Initial Sr^{87}/Sr^{86} ratio from coexisting apatite determined to be 0.7031.

TABLE 4

Strontium isotopic composition of apatites from some alkalic intrusive rocks from central and eastern United States. No correction for *in situ* radiogenic growth is necessary because of the low Rb/Sr ratios. Rubidium and strontium concentrations by X-ray fluorescence.
(Sample number: A, apatite)

Sample number	Rb, ppm	Sr, ppm	Sr^{87}/Sr^{88}
Rosiclare, Illinois, and vicinity			
197A	<10	1600	0.7030
238A	<10	1400	0.7019
Staunton, Virginia			
563A	<10	7200	0.7031
Grand Isle, Vermont			
514A	<10	500	0.7041
Average			0.703

This rather primitive strontium isotopic composition for a Phanerozoic igneous rock is similar to that found in carbonatites (Powell, Hurley, and Fairbairn, 1965), oceanic tholeiites (Tatsumoto, Hedge, and Engel, 1965), and some other basaltic rocks (Hedge and Walthall, 1963; Gast, Tilton, and Hedge, 1964; Powell, Faure, and Hurley, 1965), but it is lower than that found for Alpine-type ultramafic rocks (Roe, Pinson, and Hurley, 1965; Stueber and Murthy, 1965).

AGE RESULTS

A perusal of tables 2 and 3 will immediately show that, contrary to some earlier interpretations, the various alkalic intrusions of the Central and Eastern Interior Provinces are not all of a single, related age. Indeed, many of the local clusters of these rocks appear to represent distinct episodes of emplacement temporally unrelated to any other. Ages range from Late Ordovician to Late Cretaceous and indicate that these rocks are not unique to a specific geologic epoch. Therefore, the radiometric data will be treated on a locality basis, and a synthesis will be postponed until the section of the paper on "Regional Implications".

Silver City and Rose Domes, Kansas.—Mica peridotite crops out on the Silver City dome and occurs in the subsurface 7 miles to the northeast on Rose dome in southern Woodson County, Kansas. K-Ar ages were determined on two samples of biotite (556B, 557B) from the Silver City dome and one (703B) from the Rose dome locality. All these ages are in good agreement at approximately 90 million years. No Rb-Sr age could be obtained on these micas because of their extremely high normal strontium contents, which exceeded 0.1 percent in one sample. Wagner (1954) states that the peridotite magma from the Silver City dome "crystallized rather slowly into biotite, olivine, augite, hypersthene, apatite, and titanite, forming a medium-grained mica peridotite. Relics of the original minerals remain, but the rock is now composed mainly of phlogopite, serpentine, nontronite, illite, tremolite-actinolite, limonite, magnetite, and titanite". There is no evidence suggesting that any of the mica is xenocrystic in origin, rather it appears to have crystallized with the rest of the rock in place.

Late Cretaceous age for the intrusion of these peridotites is entirely compatible with geologic evidence which merely dates them as post-Late Pennsylvanian. Several earlier workers (Tolman and Landes, 1939) have suggested a Cretaceous age for most of the alkalic rocks of the Midcontinent by correlation with petrographically similar, stratigraphically well-dated material in Arkansas; this locality appears to be one of the few places where this correlation agrees with radiometric work. Controversy continues over the origin of the granite found as scattered boulders surrounded by Pennsylvanian sedimentary rocks on Rose dome. The discovery of mica peridotite in bore holes drilled into the dome (P. E. Franks, written communication) suggests a genetic relationship between the emplacement of the granite and the peridotite, the granite perhaps representing basement rock brought up in a peridotite pipe.

Little Rock and Magnet Cove, Arkansas.—Much literature exists about the petrography and age relationships of the syenites and peridotites of central and southern Arkansas (Williams, 1891; Miser, 1914; Miser and Ross, 1922; Ross, Miser, and Stephenson, 1929; Bramlette, 1936; Moody, 1949; Gordon, Tracey, and Ellis, 1958; and Erikson and Blade, 1963). Although the syenite at Little Rock can be geologically dated only as being late Paleozoic to Paleocene and the complex at Magnet Cove as being Mississippian or younger, a much closer stratigraphic position has been established for other alkaline rocks in the area. Relationships involving the diamond-bearing peridotites in Pike County, Arkansas, and water-laid volcanic debris in southwestern Arkansas, southeastern Oklahoma, and northeastern Texas, and drill-hole data throughout the Mississippi embayment indicate a Late Cretaceous age for most of the igneous activity. Two samples of biotite (249B, 250B) from nepheline syenite from Granite Mountain near Little Rock collected by Charles Stone were dated by both the K-Ar and the Rb-Sr methods. They yield an average date of 88 million years, in good agreement with their presumed Late Cretaceous age. Two samples of biotite (558B, 562B) from the alkalic igneous complex at Magnet Cove—one from melteigite dated by the K-Ar method and one from biotitic garnet ijolite dated by both the K-Ar and Rb-Sr methods—give an average Late Cretaceous age of 97 million years. These ages from Little Rock and Magnet Cove lie near the limits of analytical uncertainty of each other, and therefore they may represent contemporaneous or slightly different times of intrusion.

Avon, Missouri.—Kimberlite diatremes and peridotite intrusions have long been recognized from the vicinity of Avon in Ste. Genevieve and St. Francois Counties, Missouri (Weller and St. Clair, 1928, p. 249-251; Singewald and Milton, 1930; Tarr and Keller, 1933; Rust, 1937; and Kidwell, 1947). More than seventy such intrusions have been recognized ranging in composition from essentially pure mica peridotite to breccias composed entirely of sedimentary rock fragments. Although the intrusions are only observed to cut Cambrian strata, the presence of Devonian fossils in limestone xenoliths within several of the diatremes has led to a correlation of these inclusions with the Little Saline Limestone of Early Devonian age and the Grand Tower Limestone of earliest Middle Devonian age in this area (Kidwell, 1947). The igneous activity responsible for these kimberlites, therefore, must postdate the deposition of these strata. Biotites from two of the peridotite-bearing diatremes (192B, 194B) were dated by the K-Ar and Rb-Sr methods. They yield concordant dates averaging 390 million years, which suggest an Early to Middle Devonian age. This result is compatible with the geologic evidence if the diatremes were formed immediately after the Little Saline and Grand Tower Formations were deposited. The absence of distinctive Mississippian rocks in any of the diatremes has been suggested by Snyder and Gerdemann (1965) as evidence of a pre-Mississippian age for their emplacement.

The biotites in these kimberlites and peridotites occur as large, isolated flakes often somewhat fragmented in appearance and quite possibly are xenocrysts carried to their present position during the explosive activity that probably accompanied the formation of the diatremes. Because an erroneous determination of the age of emplacement might arise from excess radiogenic argon, as will be discussed for the Pennsylvania and New York localities, one might ask if a similar phenomenon was operative here. Although this question cannot be answered unequivocally, the ages determined for different samples and by different dating methods are concordant and geologically plausible. Also, no erroneous Rb-Sr ages arising from such an effect involving inherited radiogenic strontium are known for undisturbed igneous rocks.

Rosiclare, Illinois, and vicinity.—Dikes and sills of mica peridotite, kimberlite explosion breccias, and alkalic syenite intrude Mississippian and Pennsylvanian rocks in the Rosiclare fluorite district of Illinois and Kentucky. These alkalic rocks have been investigated in great detail (Weller, Grogan, and Tippie, 1952; Brown, Emery, and Meyer, 1954; Clegg and Bradbury, 1956; Heyl and Brock, 1961) because of their possible relationship with the fluorite, zinc, and lead mineralization of this district. Clegg's study (1955) of the coking properties of a metamorphosed coal adjacent to a mica peridotite dike in the district established a maximum temperature of intrusion of 600°C. Biotite and hornblende from a kimberlite (189B and H) were dated by the K-Ar method, and two biotites (197B, 238B) from a sill and a dike of mica peridotite were dated by both the K-Ar and Rb-Sr methods. All the ages lie within experimental uncertainty of each other and give an average Early Permian age of 267 million years. The kimberlite on which the mineral ages were determined consists of fragmented crystals of biotite and hornblende in a groundmass of brecciated and silicified carbonate rock. No igneous groundmass was observed, and the isolated large crystal fragments of biotite and hornblende are interpreted as xenocrysts. On the other hand, the biotite from two peridotites occurs in the groundmass suggesting crystallization after emplacement. The concordance of the ages from minerals representing both these modes of occurrence supports the conclusion that the determined age is indeed the time of emplacement of these rocks.

Elliott County, Kentucky.—Peridotite and kimberlite diatremes and dikes in Elliott County in eastern Kentucky were first described in detail by Diller (1887). More recently the investigation of these rocks has been revived by the current interest in possible mantle-derived material. Inclusions of eclogite and granulite are especially abundant in the kimberlites. Xenocrystic biotite (555(a) and (b)) was separated from the groundmass of two samples of the kimberlite from one dike, and any mica associated with the inclusions was carefully excluded. K-Ar dates from both these separates and a Rb-Sr date from one of them yield a concordant Early Permian age of 269 million years. Because of the xenocrystic nature of these micas, the same arguments for and against an inherited age as discussed for the Avon, Missouri, samples are pertinent. This age determination is similar to that obtained for the igneous rocks of the Rosiclare district, which lie at the opposite end of the Rough Creek-Kentucky River fault zone, a prominent structure in the basement and Paleozoic rocks of Kentucky.

Staunton, Virginia.—A suite of alkalic rocks ranging in composition from nepheline syenite to peridotite occurs in west-central Virginia and adjacent West Virginia (Darton, 1890, 1898; Johnson and Milton, 1955). Samples of biotite (563B) and hornblende (563H) from a dike of nepheline syenite just northeast of Staunton, Virginia, were included in this study. The syenite is medium-grained, hypidiomorphic, and equigranular in texture and is composed of orthoclase, nepheline, analcite, acmite, biotite, and hornblende with accessory natrolite, apatite, and opaques (Charles Milton and R. W. Johnson, written communication, 1965). The biotite was dated by both the K-Ar and the Rb-Sr methods, and the hornblende was dated by the K-Ar method. The two K-Ar ages are essentially in agreement at 149 million years; however, an anomalously low Rb-Sr age of 114 $\pm$ 12 million years was found for the biotite. Although no effects of metamorphism or alteration are visible in the syenite, some such process undoubtedly has disturbed this latter radiometric system. No evidence of inclusions or xenocrystic material was observed in this rock, and the K-Ar age probably represents the time of emplacement and crystallization of the dike. This age is similar to that considered by us to be the age of the kimberlite dikes in Pennsylvania and New York and the alkalic dikes along Lake Champlain in Vermont.

Beemerville, New Jersey.—A suite of alkalic rocks consisting of small stocks and dikes of nepheline syenite, tinguaite, ouachitite, and camptonite occurs in the vicinity of Beemerville, Sussex County, New Jersey. These intrusions cut sedimentary rocks of Middle Ordovician and older age but not adjacent Silurian rocks. Although this outcrop pattern might simply be fortuitous, it has previously been used as evidence of a possible Late Ordovician age for the alkalic rocks. Biotites (260B, 261B) separated from two of the intrusions were dated by the K-Ar and Rb-Sr methods and found to have an average Late Ordovician age of 434 million years, supporting the above-mentioned geologic evidence. The authigenic nature of the biotites and the good agreement of all of the radiometric ages lend further credibility to their reliableness in dating the time of emplacement of these alkalic rocks. A zircon sample from the nepheline syenite (261) was analyzed by the lead-alpha methods and yielded an age of 520 ± 60 million years (T. W. Stern, written communication, 1963). Considering the uncertainties inherent in the lead-alpha method, this age is considered to be in agreement with those determined by the K-Ar and Rb-Sr methods.

Grand Isle, Vermont.—A north-trending swarm of alkalic dikes including lamprophyres, peridotites, and syenites occurs along the Lake Champlain valley in eastern Vermont and northeastern New York (Kemp and Marsters, 1893; Shimer, 1902; Hudson and Cushing, 1931) and extends into Canada to near the central part of the Monteregian Hills. Biotite from one such lamprophyre on Grand Isle gives a K-Ar age of 136 ± 7 million years. As a result of the unfavorable Rb/Sr ratio for this mica, it was not possible to obtain a meaningful Rb-Sr age. However, because the mica occurs as an authigenic constituent of the rock and yields an age quite compatible to that of other alkalic dikes in northeastern United States and southeastern Canada, the K-Ar age is considered to indicate a reasonable time of emplacement for the dike.

Pennsylvania-New York localities.—Kimberlitic peridotite dikes occurring singly or in localized clusters have been found in western Pennsylvania and western and central New York (Smyth, 1892, 1896, 1902; Matson, 1905; Smith, 1909, 1931; Hopkins, 1914; Honess and Graeber, 1926; Newland, 1931). Because of the similarities in their petrography and the behavior of their radiometric ages, the three localities included in this study from this area are discussed together.

The kimberlites range in composition from rather unaltered olivine-pyroxene-biotite peridotites to completely serpentinized and carbonatized rock showing only relict traces of its original mineralogy. Xenoliths of the intruded Paleozoic sedimentary rocks and the underlying basement range from abundant to essentially absent. Flakes of xenocrystic biotite as large as 1 inch in diameter are almost ubiquitous in occurrence throughout the kimberlites and commonly appear to be unaltered even in the highly serpentinized material. In some of the dikes the biotite ranges down to microscopic in grain-size, and it is not clear whether this finer mica has crystallized in place or is allogenic.

Initial K-Ar analyses on separates of coarse-grained, xenocrystic biotite (259B, 190B(a), 193B(a)) gave ages that were stratigraphically too old for two of the three samples. The Masontown, Pennsylvania, dike, which cuts Upper Pennsylvanian rocks, had an apparent age of 368 ± 18 million years, and the Portland Point, New York, dike, which cuts Middle Devonian rocks, had an apparent age of 439 ± 22 million years. The sample from Manheim, New York, comes from a dike cutting Lower Devonian rocks, and while its age of 371 ± 19 million years is geologically possible, it is also considered suspect by analogy with the other cases. Because of the very high K_2O content of these micas, it would appear that the presence of radiogenic argon at the time of emplacement rather than a recent loss of potassium is responsible for these anomalously high ages. Repeat argon analyses of two samples (259B and 193B(a)) and a second separate from the other (190B(b)) showed considerable disagreement with the initial runs and suggest that the supposed excess argon content of these micas was also quantitatively highly variable. The heterogeneity in argon contents from the same separates is probably attributable to the difficulty in splitting material of such a coarse grain-size. Replicate potassium determinations on each of the mica separates failed to show a similar K_2O variation. Rb-Sr ages of 136 ± 8 and 118 ± 15 million years were obtained on samples 190(b) and 193(a), respectively, and as will be discussed subsequently possibly are quite close to the true age of these dikes.

Excess radiogenic argon has been reported previously in some minerals such as beryl (Damon and Kulp, 1958), pyroxenes (Hart and Dodd, 1962; McDougall and Green, 1964), and micas (Milashev and Shul'gina, 1959; Mikheyenko and Nenashev, 1961; Davidson, 1964; Lovering and Richards, 1964). It is of interest that the only micas with excess radiogenic argon that have been well documented occur as xenocrysts or in eclogitic inclusions from kimberlite pipes. Because of the importance of excess radiogenic argon in its bearing on both geochronology and mantle composition, this problem was pursued in some detail.

No additional material from Masontown, Pennsylvania, was available for our study; however, new samples were collected from both New York localities. An approximately 10-pound block of peridotite from each was carefully pulverized and sized so as to minimize the fragmentation of mica grains. Biotite separates from the 10 to 20 mesh and the 80 to 120 mesh fractions were obtained (190B(c) and (d)) from Portland Point and (193B(b) and (c)) from Manheim, to see if the excess radiogenic argon could be related to grain-size. Enough of the coarse-grained material was processed to make replicate argon and potassium determinations on carefully prepared sample splits. As shown by table 2, the results of these more detailed analyses permit the following conclusions.

1. The coarse-grained biotite from Portland Point (190B(b)) continues to show an anomalously old K-Ar age, quite incompatible with its known stratigraphic relationship. Also, the discordancy between K-Ar and Rb-Sr ages remains unresolved in both of these samples. A second Rb-Sr age was determined on the coarse biotite from the Manheim sample (193(b)). Because the mica proved to have a more radiogenic strontium than the initial one from this locality, this age of 146 ± 8 million years is considerably more precise than the former.

2. Even under very controlled conditions employing a multichannel aluminum splitter, variation of as much as 9 percent occurred between repeat argon extractions of sample 193B(b). This variation is over five times that found for normal, homogeneous samples analyzed in the same laboratory. Of additional interest is the fact that the extraction yielding the greatest argon content is the only one in which an overnight bakeout of the sample at 300°C was employed. If the excess radiogenic argon resides in some lattice defects or fluid inclusions (Hart and Dodd, 1962; Funkhouser, Naughton, and Barnes, 1965) within the mica, there is no evidence from this experiment that it is easily released at low temperatures. Unlike the argon, replicate potassium determinations were reproducible to within 1 percent on separate splits of each sample.

3. Quite a different picture emerges from the K-Ar analyses of the fine-grained biotite. In this case ages of 145 and 150 million years are obtained on samples 190B(d) and 193B(c), respectively. In view of the uncertain paragenesis of this fine-grained mica, it is not known if these apparent ages represent those of an authigenic mineral in the peridotite or of xenocrystic inclusions merely containing less excess radiogenic argon than the coarse-grained material. If the fine-grained mica has crystallized in place, this age may correctly date the emplacement of the dike, whereas if it is allogenic one can only use the age as a maximum because it is not known to be completely devoid of excess radiogenic argon. Nevertheless, the rather close agreement between these ages and those obtained by the Rb-Sr method on the coarse-grained biotite, coupled with the occurrence of other well-documented Lower Cretaceous to Upper Jurassic alkalic intrusions in northeastern United States and adjacent Canada (Fairbairn and others, 1963; Faul and others, 1963; Wanless and others, 1965), leads us to place some credibility on this age.

Attempts to date the fine-grained mica by the Rb-Sr method proved unsuccessful because of unfavorable Rb/Sr ratios. It might be mentioned that in several instances throughout this study where more than one mesh size of mica from a given sample was X-rayed, the Rb content remained essentially constant while the Sr content increased greatly with decreasing grain-size. Impurities in the mineral separates did not appear to be responsible for this effect.

We conclude that the presence of excess radiogenic argon in some of these mica peridotites from Pennsylvania and New York has been unequivocally proven. The origin of such excess radiogenic argon has been discussed in some detail by Lovering and Richards (1964), who suggest that, "these great ages may result from excess radiogenic Ar incorporated in the mineral lattice under conditions of locally high Ar partial pressures. These conditions could have existed either within the mantle (if the xenoliths are of accidental origin) or at depth in the host magma (if cognate)". Although these authors were chiefly concerned with eclogitic and granulitic xenoliths, most of the arguments presented by them are equally valid for the phlogopite xenocrysts studied in this paper. Davidson (1964) interprets the radiometric data from some Siberian kimberlites found in Yakutia Province to indicate a two-state formation. He deduces a lower Sinian (around 650 m.y.) emplacement of an original body of massive kimberlite into the crust followed in Mesozoic time by brecciation and fluidization to form the present-day exposed pipes. Low temperatures and high gas pressures at the time of final intrusion are called upon to preserve the older K-Ar ages found in micas from the breccia.

Assuming an Early Cretaceous age of intrusion for the Pennsylvania and New York dikes, we are dealing with quantities of excess argon^{40} of the order of 3 to 13 x 10^{-5} ccSTP/gm in these micas. This quantity of gas exceeds that found previously in various minerals of low potassium content and further points out some of the unique characteristics associated with the peridotite genesis. Whether the excess radiogenic argon reflects a relict age of some precursor material from which the mica was derived but not degassed, or whether it resulted from some external partial argon pressure forcing the gas into the mica cannot be resolved by the present study. If this excess does indicate the presence of radiogenic argon in the mantle or lower crust, some knowledge of the partition of this gas between melt (?) and biotite would be useful in placing limits on the degassing of the Earth.

REGIONAL IMPLICATIONS

The K-Ar and Rb-Sr age determinations indicate that alkalic igneous activity took place in the central and eastern United States from late Ordovician to late Cretaceous time. Several distinct periods of intrusion during this time interval are indicated by the radiometric ages in different parts of the region.

The peridotites in Rose dome and Silver City dome (fig. 1) in southeastern Kansas give K-Ar ages that are late Cretaceous. These results are similar to the radiometric ages found near Little Rock and Magnet Cove, Arkansas, and to the geologically dated kimberlite diamond pipes of Murfreesboro, Arkansas.

The Rose dome and Silver City dome intrusions are at the western end of a structural lineament described by Snyder and Gerdemann (1965) and Heyl and others (1965, p. B5-6, fig. 2). This line of faults and structures extends eastward across Missouri just south of the 38th parallel of latitude to the dike swarm near Avon, Missouri, in the northeastern part of the southeast Missouri lead district. Snyder and Gerdemann (1965) describe two centers of Cambrian volcanic activity near Hazel Green and at Furnace Creek near Hunters Mills, Missouri, along the line west of Avon.

The kimberlite dike and diatreme sampled near Avon give concordant Middle to Early Devonian radiometric ages by K-Ar and Rb-Sr analyses. These ages are in good agreement with geologic evidence provided by inclusions of limestone and chert fragments in some of the intrusions that contain identifiable Devonian fossils (Kidwell, 1947, p. 33). Also, the intrusions lie at the crest of the fractured and brecciated Farmington anticline near the intersection of the 38th parallel lineament and the northwest-trending Ste. Genevieve fault zone. The Ste. Genevieve fault zone began developing in Devonian time (Weller and St. Clair, 1928) as probably did the related fractured area, thus providing likely deep-seated access channels for the intrusions.

About 100 miles east of Avon, in southeastern Illinois and western Kentucky, is a large area of mafic alkalic dikes and diatremes centered about Hicks dome, Hardin County, Illinois, which is in the north-central part of the Illinois-Kentucky fluorite-zinc-lead district. The intrusions lie at the intersection of the eastward trending line of faults along the 38th parallel with a broad northeastward-trending zone of faults, the New Madrid fault zone (Heyl and Brock, 1961). The dike, sill, and diatreme sampled in the Illinois-Kentucky district give K-Ar and Rb-Sr age determinations that indicate alkalic igneous activity in Late Pennsylvanian and Permian times, a date that agrees well with the geologic history (Weller, Grogan, and Tippie, 1952; Heyl and Brock, 1961). The most probable initial development of the ancestral dome of the district was in Late Pennsylvanian and Permian times; the dikes are known to be restricted usually to northwest-trending faults and fractures, the oldest of the several trends developed in the dome. The age of the closely associated mineral deposits is established as post-dike and post-Pennsylvanian but pre-Late Cretaceous (Bastin, 1939) and thus further confirms the radiometric age determinations.

The line of faults that follows the 38th parallel extends eastward from Illinois across the entire length of Kentucky as the Rough Creek-Shawneetown fault zone and then the Irving-Paint Creek fault zone. In Elliott County, eastern Kentucky, a small swarm of kimberlite intrusions lies along the northern edge of the fault zone. These kimberlites intrude shales and sandstones of Pennsylvanian age (Diller, 1887; Koenig, 1956) and give K-Ar and Rb-Sr ages that are Late Pennsylvanian and Permian, similar to the ages determined in the Illinois-Kentucky district along this same lineament to the west.

A very extensive eastward-trending elongate group of intrusions, many of which are felsic and mafic alkalic rocks, lies in eastern West Virginia and in the Shenandoah Valley of western Virginia near Staunton (Johnson and Milton, 1955) along the less well-defined eastern extension of the structural lineament along the 38th parallel. The swarm of intrusions in the Shenandoah Valley lies within the southern part of the Timberville zinc district. The dikes have long been assumed to be of Triassic age (Darton, 1898) because some of them are diabases and basalts similar to rocks found in the Triassic basins to the east. The K-Ar and Rb-Sr ages of biotite and the K-Ar age of hornblende from a nepheline syenite dike in the east-central part of this group of intrusions suggest a Jurassic to Cretaceous age for at least some of the intrusions.

An isolated suite of alkalic rocks occurs in the vicinity of Beemerville in northwestern New Jersey. Radiometric data for two of the intrusions give concordant K-Ar and Rb-Sr biotite dates of late Ordovician age, in agreement with the geologic relationships.

The intrusions along Lake Champlain Valley and in central and western New York have a Jurassic-Cretaceous radiometric age rather similar to those determined previously (Fairbairn and others, 1963) for the Monteregian Hills of southeastern Quebec and in this paper for the Staunton, Virginia, locality. A difficulty exists in interpreting the age data for the New York dikes due to the presence of excess argon in their coarse, xenocrystic biotites. We believe, however, that the Rb-Sr ages from these micas coupled with the K-Ar ages from the fine-grained mica fraction correctly date the time of emplacement of these dikes as early Cretaceous to Jurassic.

Only K-Ar ages on xenocrystic biotite from a cluster of dikes in western Pennsylvania were determined. Because of the presence of excess radiogenic argon in this mica, no definitive radiometric age could be obtained. Geologically, these intrusions are probably a southwestern extension of the New York dikes and may indeed be of a similar age.

The Jurassic and Cretaceous radiometric ages in Vermont, New York, Virginia, and southeastern Quebec indicate that a period of alkalic intrusions and volcanism followed the emplacement of diabases and basalts in Triassic time, which was long considered to be the final period of igneous activity in the East. Therefore, sporadic igneous activity continued in the East for at least 50 million years longer during most of the Mesozoic Era.

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