

## NEW PHLOGOPITE K-Ar DATES AND THE AGE OF SOUTHWESTERN PENNSYLVANIA KIMBERLITE DIKES

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**ABSTRACT:** The Masontown, Fayette County, and Dixonville/Tanoma, Indiana County, Pennsylvania, dikes cut Pennsylvanian and lowermost Permian(?) sedimentary rocks. They are composed of a fine-grained matrix of calcite, serpentine, phlogopite, opaque oxides, apatite and sulfides. Phenocrysts (<1cm) and megacrysts (>1 cm) are olivine, phlogopite, pyrope garnet and ilmenite, some pyroxenes are found in the Dixonville/Tanoma. Xenoliths of mantle and crustal origin are also present.

New conventional K-Ar dates for the Masontown kimberlite are as follows: coarse phlogopite megacrysts,  $353 \pm 2.2$  Ma; fine-grained phlogopite from the groundmass [in an internal contact zone],  $147.3 \pm 1.5$  Ma; and olivines [run as a check for excess argon], *ca* 280 Ma. A single phlogopite date of  $349.6 \pm 1.5$  Ma was determined for the Tanoma/Dixonville dike.

Rb-Sr mineral dates for megacryst and fine-grained phlogopites from the Masontown dike are  $188.0 \pm 0.7$  Ma and  $170.1 \pm 1.3$  Ma respectively, using initial ratios from calcite and garnet. A Sm-Nd scatterchron date is *ca* 145 Ma [i.r. = 0.51284].

The Masontown kimberlite was emplaced in late Jurassic time, possibly preserving an Acadian argon signature in coarse phlogopites, and early Jurassic argon and strontium isotopic systematics in some phlogopites. Final emplacement during the late Jurassic, determined by the Sm-Nd scatterchron and fine-grained phlogopite K-Ar dates, was into an existing zone of crustal weakness, and occurred with few or no contact effects.

### INTRODUCTION

The Masontown, Fayette County, kimberlite dike (Fig. 1) cuts uppermost Pennsylvanian and lowermost Permian(?) rocks of the Uniontown and Waynesburg formations, the youngest pre-Pleistocene sedimentary rocks in the region. The Dixonville/Tanoma [D/T], Indiana County, dike swarm is found only in underground coal mines [Barr Slope and Tanoma], where it cuts through Lower Kittanning coal and other Allegheny Group [upper-middle Pennsylvanian] rocks. These dikes are the only igneous rocks known in western Pennsylvania, and are two of several silica-poor, alkaline intrusions in the Appalachian Plateau (Deines 1968) associated with the formation of the Appalachian Mountains (Parrish and Lavin 1982; Taylor 1984; Shervais et al. 1987; McHone 1992). The other known intrusions include kimberlites in New York, Maryland, Virginia, Tennessee and Kentucky, and lamproites in Arkansas.

The purpose of this paper is twofold: 1. to constrain the timing of the tensional stress(es) accompanying the formation of the post-Pangea Atlantic Ocean by dating the dikes, and 2. to attempt to use the isotopic signatures to help understand kimberlite emplacement. This is a preliminary report of an ongoing study.

Previous work on the Masontown dike [also known as the Fayette County, Nemacolin mine, Gates or Adah dike] includes early field and petrographic descriptions by Kemp and Ross (1907), Smith (1912) and Hickok and Moyer (1940) summarized in a structural study by Roen (1968). Roen described the dike as intruding a N51°W strike-slip fault zone of small left lateral displacements, extending 11 kilometers with a width ranging up to 152m. This fracture zone cross-cuts

the regional folding, and was associated with the Jurassic opening of the Atlantic Ocean by Parrish and Lavin (1982). Chemical and petrologic studies of the Masontown kimberlite have been made on garnet (Hunter and Taylor 1982), phlogopites and oxides (Hunter et al. 1984; Weise et al. 1996), various megacrysts (Hunter and Taylor 1984), xenoliths (Prellwitz and Bikerman 1994), and general petrography (Prellwitz and Bikerman 1993). The chemical and mineralogical data from the Masontown dike, along other kimberlites from the eastern United States, were used in a genetic model of two magmas mixing in the Low Velocity Zone (LVZ) by Hunter and Taylor (1984) and Shervais et al. (1987).

The D/T dike was originally encountered in the Barr Slope Mine at Dixonville, and described by Honess and Graeber (1926). It was rediscovered in the Tanoma Mine, which lies 2 km west of the Barr Slope mine (Tedeski, personal communication 1993, Mbala-Keswa et al. 1994).

K-Ar dates of  $368 \pm 18$  and  $408 \pm 20$  Ma (Zartman et al. 1967) on phlogopites from the Masontown dike were attributed to excess argon or inherited megacrysts; and a phenocryst phlogopite K-Ar date of  $184 \pm 10$  (Pimentel et al. 1975), was considered to be geologically reasonable. The latter also reported a <sup>87</sup>Sr/<sup>86</sup>Sr initial ratio of 0.7008 (recalculated to modern constants) on a whole rock sample. Alibert and Albarede (1988) dated the Masontown dike at  $149 \pm 5$  Ma, and the Dixonville dike at  $89 \pm 5$  Ma by Rb-Sr. Bikerman et al., (1994 a & b) presented additional preliminary isotopic data on the Masontown dike.

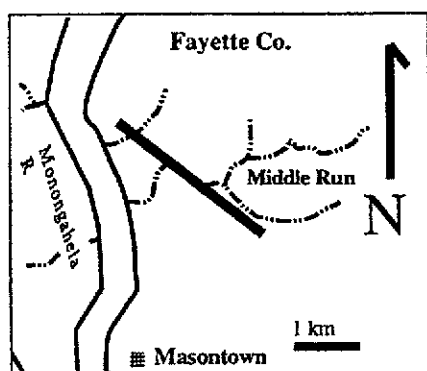
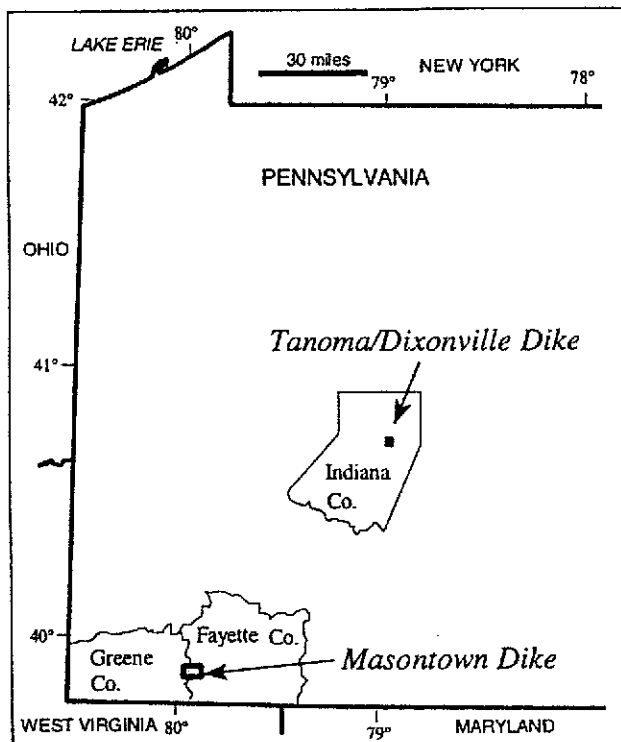


Figure 1. (a) Location map of Masontown and Dixonville/Tanoma (D/T) Dikes. (b) The Masontown dike outcrops sporadically along the heavy black northwest trending line in Greene and Fayette Counties.

#### PETROGRAPHY OF THE MASONTOWN DIKE

The Masontown kimberlite dike is composed of a fine grained matrix of calcite, serpentine, phlogopite, opaque oxides, apatite and sulfides. Weise, et al., (1996) have found quartz and microcrystalline silica in samples collected in the Nemaocolin mine. Phenocrysts and megacrysts (>1 cm) are olivine, phlogopite, pyrope garnet and ilmenite. Xenoliths of mantle and crustal origin are also present (Prellwitz and Bikerman 1994; Prellwitz, MS thesis 1994).

Classification of this rock into either the Group I or II kimberlites (orangeites in the terminology of Mitchell 1995) of southern Africa (Smith 1983, 1994; Wilson 1989; Mitchell

and Bergman 1991) is problematic. Hypabyssal Group I kimberlites, similar to oceanic island basalt in origin, have abundant olivine, phlogopite only as macrocrysts and phenocrysts, variable amounts of serpentine, spinel, perovskite, ilmenite, monticellite and zircon present, and rare diopside megacrysts. The phlogopites follow an Al enrichment trend, and spinels may have significant magnesian ulvöspinel content (Mitchell 1995). Group II kimberlites (orangeites) are LIL-enriched rocks and have abundant phlogopite in the groundmass along with carbonates, apatite, serpentine and spinel. They also have macro- and phenocryst phlogopite and olivine, sometimes diopside, little perovskite or ilmenite, and no zircon (Wilson 1989, Mitchell and Bergman 1991, Mitchell 1995). Compared with Group I kimberlites they have more apatite, a finer groundmass, and less perovskite and spinel, with the spinel having distinctly more Cr and less Al (Mitchell 1995).

The Masontown kimberlite has abundant phlogopite as megacrysts, phenocrysts and groundmass laths. It also has ilmenite, rare perovskite, no zircon, and no pyroxenes except for inclusions in olivine phenocrysts and in ultramafic (Iherzolite) xenoliths. Olivine phenocrysts and megacrysts in the Masontown dike are usually rounded with unidentified opaque black rims. Some olivines are fresh in appearance, some are strained, and many show some degree of alteration to serpentine. Olivines near calcite veins are totally serpentinized. Megacrysts range up to 5 cm in long dimension and often are aligned with the flow direction. Hunter and Taylor (1984) divided the megacrysts into Cr-rich and Cr-poor populations based largely on the chemical composition of garnets. Cr-rich garnets have 1.64 to 6.14%  $\text{Cr}_2\text{O}_3$  and Cr-poor have <0.1%  $\text{Cr}_2\text{O}_3$ . Optical determinations agree with the chemical data of Hunter and Taylor (1984) that olivines in the Cr-rich suite are more Mg-rich in their cores [Fo90-93] than those in the Cr-poor suite [Fo81-85], whereas the rims of all the olivines are Fo88-89. The smaller phenocrysts are all in the Cr-rich group, while megacrysts were in both groups. Some olivine crystals have 0.2-4 mm inclusions of orthopyroxene. The olivines used for K-Ar dating came from the phenocryst and megacryst population of fresh appearing olivine.

Phlogopites are abundant in the Masontown dike as megacrysts and as fine-grained components of the groundmass. The megacrysts are coarse (up to 3.7 cm long), rounded, oblate, and slightly abraded at the edges. The groundmass phlogopites are mostly euhedral, fine grained 0.1-0.25 mm crystals, with finer ( $10 \times 100 \mu\text{m}$ ) laths found in an internal contact zone between the Cr-rich and Cr-poor suites of Hunter & Taylor (1984). Aside from occasional chloritization, the phlogopites are not altered. In the Nemaocolin mine samples, Weise, et al., (1996) have identified six varieties of mica: 1) small matrix laths probably similar to the contact zone ones; 2) macrocrysts; 3) macrocrysts with cores high in Mg and Si, but low in Ti, Al and Cr; 4) reddish-brown biotite - phlogopite macrocrysts; 5) clusters of interlocking phlogopite crystals [glimmerites]; and 6) kelyphitic rims on garnets.

Table 1. K-Ar results for the Masontown (M) and D/T dikes.

Sample	K %	Atmos. <sup>40</sup> Ar %	Rad. <sup>40</sup> Ar moles	Date Ma
M coarse phlogopite	7.82	14.5	5.29x10 <sup>-9</sup>	353±2.2
M fine phlogopite	7.06	9.1	1.88x10 <sup>-9</sup>	147.3±1.5
M olivine	0.175	13.06	9.08x10 <sup>-11</sup>	(277)
D/T phlogopite	8.03	4.25	5.671x10 <sup>-9</sup>	349.6±1.5

Hunter and Taylor, (1984) identified two populations of pyrope garnets: a dark red, low-Cr type and a paler orange, high-Cr type. Most of the garnets are spheroidal, range in size from 1 mm to 1 cm, and exhibit kelyphitic rims of various widths. Glass in these rims was attributed to incongruent melting of the garnets (Hunter and Taylor 1982). In addition, a few garnets were found in the lherzolite xenoliths.

Ilmenite megacrysts are black, range in size from 3 mm to over 2 cm, and usually are unaltered, elongated, rounded crystals. Compositionally, these are largely picroilmenite and have spinel and perovskite reaction rims (Hunter et al. 1984). Groundmass ilmenite is intimately bound with spinel and may be rimmed with perovskite (Hunter et al. 1984). Priderite [(K,Ba)<sub>1-3</sub>(Ti,Fe<sup>3+</sup>)<sub>8</sub>O<sub>16</sub>] was identified by Weise, et al. (1996) in the Nemacolin mine sample.

Primary calcite is abundant (up to 40% of the groundmass) as a cloudy, brownish mass not amenable to good optical analysis, which led Hickok and Moyer (1940) to consider it a secondary alteration product. Comparisons with other kimberlites (Dawson 1980; Hunter and Taylor 1984; Hunter et al. 1984; Mitchell 1995) and the low initial <sup>87</sup>Sr/<sup>86</sup>Sr (Bikerman et al. 1994b) argue for an igneous origin for the calcite. Secondary calcite is found as veins and replacements of serpentine. Fine grained (ca 0.5 mm) euhedral magnetite, random euhedral crystals (0.1 - 1 mm) of perovskite, and apatite are found in the dike.

Contact phenomena, such as baking of the country rock or chilled margins in the dike, are poorly developed. Visible contacts with shale and limestone are sharp with essentially no contact metamorphism. A temperature of 600°C was estimated on an exposure of the dike in a coal mine, based on the observed coking (Sosman 1938). Weise (personal communication 1996) found alteration temperatures of about 300°C in the coal around the thin dike within the Nemacolin mine.

#### PETROGRAPHY OF THE DIXONVILLE/TANOMA DIKE

The Dixonville dike originally described as a mica peridotite with abundant mica [larger biotite and smaller phlogopite phenocrysts], contains altered olivine and a few pyroxenes in a matrix of serpentine, dolomitic carbonate and Fe and Ti oxides (Honess and Graeber 1926). Chan (1992) identified

phenocrysts of forsteritic olivine, containing Ni, Mn, and Ca in small amounts, and high-Cr [Cr<sub>2</sub>O<sub>3</sub> > 1.7%] and low-Cr [Cr<sub>2</sub>O<sub>3</sub> < 0.5%] phlogopites, as well as groundmass monticellite and metamorphic wollastonite in the dike.

J.R. Tedeski (1994, unpublished m.s.) using samples from the Tanoma mine, identified phenocrysts of chrome diopside, phlogopite and pyrope garnet in a matrix largely made of serpentine and carbonate that contains small crystals of spinel, altered olivine, mica, garnet and serpentine. Phenocrysts of Ti-rich phlogopite and some Ti-rich pyrope garnets, and both Cr-poor and Cr-rich pyroxenes were reported by Mbalu-Keswa, et al. (1994), as well as sedimentary and occasional igneous xenoliths, up to 10 cm in diameter. The Tanoma mine also has thin contact zones, except in the coal seams where the dike flowers out, as photographed and discussed by Tedeski (1994, unpublished m.s.).

#### ISOTOPIC RESULTS

Conventional K-Ar dating (Bikerman 1972) was used, in which argon was analyzed by isotope dilution mass spectrometry on an AEI MS-10 with Kratos electronics, using a <sup>38</sup>Ar+<sup>39</sup>Ar spike from the University of California, Berkeley, CA, and K by atomic absorption. Table 1 shows the results on coarse phlogopite megacrysts, fine-grained groundmass phlogopite collected in an internal contact zone, and on unaltered olivine phenocrysts [as a check for excess argon] from the Masontown dike, and on 80-100 mesh phlogopite from the D/T dike.

The olivine argon analysis had less <sup>36</sup>Ar than spike, within error, so no date could be determined. A model date calculated using a "reasonable <sup>36</sup>Ar" is shown in parentheses in Table 1. The date for a 100% radiogenic <sup>40</sup>Ar run (no <sup>36</sup>Ar from air present) would be 319 Ma. In neither case is there evidence for excess argon in the olivine.

Rb-Sr and Sm-Nd isotopic analyses (Bikerman et al. 1994b) are in Table 2 and plotted in Figure 2, along with the isotopic data of Alibert and Albarede (1988), and the fields of Group I and Group II southern African kimberlites (Smith 1983, 1994; le Roex 1986). As with the petrographic descriptions, the Masontown dike does not fit within either of these groups. The analyzed minerals and the host rock are not in isotopic equilibrium (Bikerman et al. 1994b). Calculated Rb-Sr mineral dates for the megacryst (*mc*) and fine-grained

Table 2a. Isotopic measurements on samples of the Masontown dike Rb-Sr, measured and initial  $^{87}\text{Sr}/^{86}\text{Sr}$ , and epsilon values.

Sample	Rb ppm	Sr ppm	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}}$	$\epsilon_{\text{Sr}}$
whole rock	65.8	1470.4	0.70540	0.13	0.70513	11.4
calcite vein	6.5	860.2	0.70369	0.022	0.70365	-9.7
Cr-rich garnet	1.08	11.2	0.70472	0.28	0.70414	-2.7
Cr-poor garnet	0.11	1.91	0.70470	0.16	0.70437	0.5
phlogopite <i>mc</i>	847.	97.7	0.77142	25.27		
phlogopite <i>gm</i>	557.	120.	0.73646	13.47		

Note: *mc* = megacryst *gm* = groundmass

Table 2b. Sm-Nd analyses and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios and epsilon values.

sample	Nd ppm	Sm ppm	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_{\text{initial}}$	$\epsilon_{\text{Nd}}$
whole rock	73.7	10.5	0.51288	0.51280	6.8
calcite vein	17.7	1.99	0.51293	0.51287	8.1
Cr-rich garnet	0.87	0.84	0.51335	0.51279	6.7
Cr-poor garnet	0.82	0.61	0.51333	0.51290	8.8

phlogopites (*gm*), using the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios from the calcite vein and garnets, range from 187.3 to 188.6 Ma and 168.8 to 171.4 Ma respectively. The high  $^{87}\text{Rb}/^{86}\text{Sr}$  makes the dates relatively insensitive to the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio chosen for the initial daughter correction. A four point Sm-Nd scatterchron date (Fig. 3) is  $145 \pm 11$  Ma [i.r. =  $0.51284 \pm 0.00003$ ], with MSWD = 16.5.

The low initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio in the calcite vein precludes its origin from limestone and is consistent with an igneous source, though not from the surrounding carbonate, which has a slightly higher  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio. The matrix carbonate also has too low a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio to be derived from limestone.

DISCUSSION

If the age of emplacement of the Masontown kimberlite is ca 147 Ma, using the K-Ar date of the fine-grained Masontown phlogopite, the Alibert and Albarede (1988) Rb-Sr date and the Sm-Nd scatterchron date, which is in the late Jurassic→early Cretaceous range of ages of kimberlite and alnoite dikes in New York state (Zartman, et al. 1967; Kay and Foster 1986), then the other dates calculated are anomalously old. It can be argued, on isotopic grounds, that the 188 Ma coarse-grained phlogopite Rb-Sr date, which agrees with the  $185 \pm 10$  Ma Pimentel et al. (1975), mean K-Ar phlogopite date, is a more likely emplacement time for the dike. If so, then the 147 Ma date is a closure date for the argon system in the fine-grained

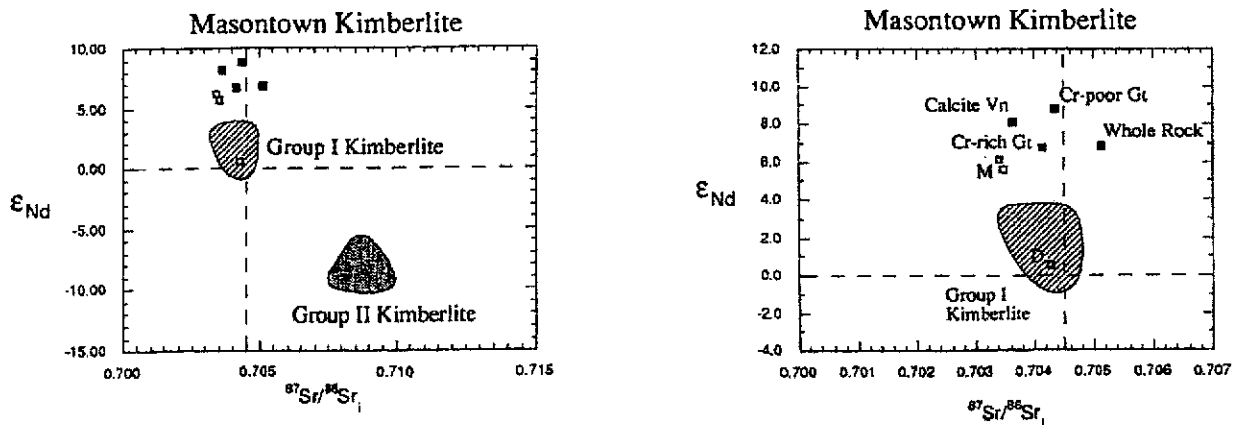


Figure 2. (a)  $\epsilon_{\text{Nd}}$  vs initial  $^{87}\text{Sr}/^{86}\text{Sr}$  of Masontown dike samples [solid squares], data from Bikerman et al., (1994b), open squares (Alibert and Albarede, 1988), and the Group I and II kimberlites of southern Africa (Smith, 1983). (b) Enlargement of upper part of 2a showing sample identification. Two open squares marked M are Masontown dike and that marked D is Dixonville.

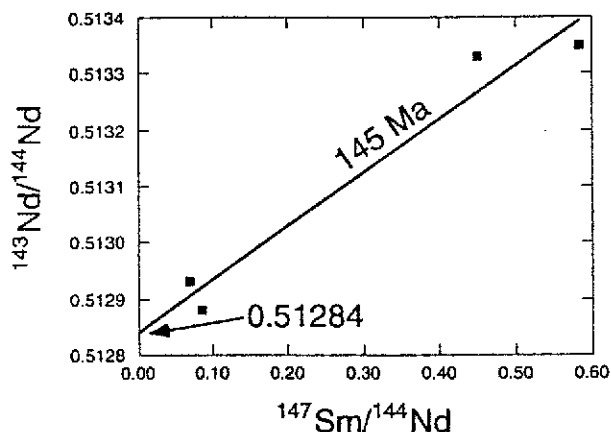


Figure 3. Sm-Nd scatterchron plot of the Masontown Dike samples [solid squares].

phlogopite. This could be either the time of intrusion of a later phase of the dike, consistent with the formation of the internal boundary within the existing dike, or the time that already formed fine grained phlogopites cooled through the argon retention isotherm, allowing them to retain radiogenic Ar. The Alibert and Albarede (1988) Rb-Sr date and the Sm-Nd scatterchron date, while not precise, is additional evidence that the 146 Ma event may be genuine. The 170 Ma Rb-Sr date of the fine-grained phlogopites is intermediate between the 147 Ma K-Ar date of the fine-grained phlogopite and the 185-8 Ma phlogopite K-Ar (Pimentel et al. 1975) and Rb-Sr dates reported on here. It may represent an earlier closure of the Rb-Sr isotopic clock than the K-Ar system in fine phlogopites, or a (partial) resetting of the Rb-Sr system by a later event.

The opening of the Atlantic Ocean throughout Jurassic time (Parrish and Lavin 1982) provided the tensional fractures to host the kimberlite dike. If the continuous opening was actually a series of episodic lurches, then the various dates may represent multiple emplacements of kimberlite in the same zones of weakness. The internal contact found in the Masontown dike is mute physical evidence for such multiple emplacement, and the lack of isotopic equilibrium is congruous as well.

The lack of excess argon in the olivine is evidence that a high pressure of argon did not exist in the magma chamber which produced the kimberlite dike. Excess argon has been reported in olivine crystals from young lavas [Damon et al., (1967); Krümmenacher, (1970); and Chen et al., (1988)], and olivine and clinopyroxene xenocrysts [Horn and Müller-Sohnius (1988); Müller-Sohnius et al., (1989)], hence its absence here is consistent with the Acadian coarse phlogopite dates being retention dates. The Zartman et al., (1967) dates are earlier Acadian dates, while the new megacryst phlogopite dates on both dikes are late or post-Acadian (Aronson and Lewis 1994). Formation of these micas was in a slow cooling to static thermal environment (hence large crystals) with no extended periods of sufficiently high temperature to produce significant

Ar loss prior to incorporation into the rising kimberlite during the late Jurassic. An alternate explanation might be that sufficient argon was moved from the megacrysts to make any age assignment meaningless.

Possibly the Acadian megacryst phlogopites may have been preserved, with little argon gain or loss, along with early Jurassic phenocrysts, in a long-lived reservoir (Roden and Murthy 1985) prior to emplacement in late Jurassic time with a new generation of fine-grained phlogopites. The temperature of such a long-lived deep source must have been relatively low for the argon generated in the mica not to have escaped. Conventional mica closure temperatures of about 300°C would seem most unusual for such a chamber, but the possibility that higher closure temperatures (>450°C) exist in natural systems (Villa and Puxeddu 1994) suggests a more reasonable chamber temperature. In the Kaapvaal craton of South Africa, Smith et al., (1994) measured a retention date of 2250 Ma in a phlogopite from a peridotite xenolith within a kimberlite [intermediate between the Groups I and II] emplaced about 140 to 170 Ma ago.

Laser spot fusion measurements on individual mica grains (Phillips and Onstott 1988, Hames 1994; Hodges et al. 1994a and b) have shown a pattern of higher ages in the center of such grains, with decreasing dates outward. K-Ar dates for phlogopites of mantle origin from African kimberlites are often older than the known age of eruption (e.g. Kaneoki and Aoki 1978; Smith et al. 1994), as is the case for the coarse phlogopite K-Ar dates for the southwestern Pennsylvania dikes. The disturbed  $^{40}\text{Ar}/^{39}\text{Ar}$  vs percent  $^{39}\text{Ar}$  released spectra found in  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of phlogopites, have been interpreted as a combination of excess initial argon, followed by later loss of argon by diffusion during the cooling process (Phillips and Onstott 1988, and references there-in). The interior of a single phlogopite grain from a garnet-lherzolite from the Premier kimberlite of South Africa, used in the laser-probe traverse of Phillips and Onstott (1988), had dates up to 2.3 Ga, older than the time of emplacement [ca 1.2 Ga] as determined in the outer portions of the crystal. The inner high dates are considered to be excess argon and in that case to have no geologic meaning. In the laser mapping done by Hames (1994) and Hodges et al. (1994 a and b), the older dates in the center of their micas were geologically reasonable and the gradients were attributed to cooling. Integrated mineral dates in all of these cases are intermediate, and should be comparable to conventional K-Ar dates as reported here. Laser mapping on the dike phlogopites will be pursued.

Evidence for the thickness of overlying material removed and the corresponding thermal regimes which must have existed since the Jurassic in the Appalachians comes from sedimentological (e.g. Friedman 1987a and b; Sevon 1994), fission track (e.g. Roden and Miller 1989), and coal (Zhang and Davis 1993) studies. Maximum depths of burial for Devonian strata are estimated to be 6.5 km in the northern Appalachians (Friedman 1987), while Pennsylvanian sedi-

mentary rocks have had at least 3.4 km of burial (Roden and Miller 1989). The fission track study of Roden and Miller (1989) shows that there is a discontinuity in the thermal regimes between the eastern Appalachians and western Allegheny Plateau areas. The eastern Appalachians had a single cooling pattern from temperatures of  $>110^{\circ}\text{C}$  in middle Jurassic through early Cretaceous. The plateau had an orogenic heating event [ $<200^{\circ}\text{C}$ ] prior to 250 Ma and a heating event in the late Jurassic to early Cretaceous which kept temperatures in the  $80^{\circ}\text{C}$  range. This heating was correlated to the timing of the kimberlite intrusions by Roden and Miller (1989). Zhang and Davis (1993) estimate the depth of Permian strata removed as about 2.6 km, maximum burial depth  $>3$  km, and a geothermal gradient during the Alleghenian orogeny of  $28^{\circ}\text{C}/\text{km}$ , in the western region of Pennsylvania.

The  $>3$  km of overburden at the time of dike emplacement undoubtedly was critical in the development of the intrusion from both shape and geochemical standpoints. The thick overburden prevented the relatively small fluidized kimberlite from exploding into a diatreme and forced the intrusion into a pre-existing tectonic plane of weakness (Roen 1968). The role of the overburden in the geochemistry is more complex. First, despite the insulating effect of the sedimentary cover, enough heat must have been lost to keep the temperatures below the closure point of phlogopite at the pressures which existed at the time. Second, the fluid content must have been low enough to prevent equilibration of the Rb-Sr systematics during the 200 Ma hiatus. Third, the overburden contained the  $\text{CO}_2$ -bearing fluid, permitting the formation of primary carbonate. While the geochemistry and mechanism(s) of kimberlite emplacement are largely unknown, most models (e.g. Mitchell 1995) require  $\text{CO}_2$  as a major component. Some of the  $\text{CO}_2$  is lost during the intrusion, while the remainder probably goes into the primary carbonate matrix minerals. Detailed discussion of emplacement is beyond the scope of this paper, and the interested reader is referred to Mitchell (1995) for a recent summary.

### CONCLUSIONS

The complex series of steps which lead to the kimberlites of southwestern Pennsylvania began with, or before the Acadian orogeny with the formation of coarse phlogopite in an unknown deep crustal or upper mantle chamber. Alleghenian orogeny collisional events, which formed the Appalachian Mountains, left no discernable evidence, but the post-Alleghenian Mesozoic Atlantic-forming tensional regime, and later epeirogenic upwarps of the Appalachians, have imprinted the unequilibrated isotopic signatures reported here.

The most likely model for the Masontown dike formation includes the following steps:

1. Acadian formation of coarse phlogopites and other minerals. The sources of the minerals were largely in the LVZ (Hunter and Taylor 1984).
2. Cooling below argon retention temperatures, ca  $450^{\circ}\text{C}$  as evidenced in the coarse phlogopites.

3. Early Jurassic opening of the Atlantic Ocean, with coeval formation of phlogopite. This process taking place more rapidly, hence finer grained crystals of mica.
4. Kimberlite dike was rapidly emplaced in two or more pulses within an existing fracture zone in the Late Jurassic. The dike entrained older phlogopite megacrysts and xenoliths, and grew fine-grained phlogopites within a carbonate-rich groundmass.
5. The relatively low temperature emplacement produced little contact metamorphism and degassing of the older mica crystals. The Masontown kimberlite emplacement mixed older megacrysts with new phenocrysts and groundmass so quickly that neither chemical or isotopic equilibrium was reached.

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