The Geology, Petrology, and Elemental Composition of Kimberlites from Riley and Marshall Counties, Kansas, USA

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Abstract

Thirteen kimberlites in Riley and Marshall counties, Kansas, have been discovered at the surface or in the subsurface by drilling into magnetic anomalies. These kimberlites are contaminated by varied amounts of mostly crustal xenoliths (mostly shales and limestones). The Swede Creek, Randolph #1, Randolph # 2, Leonardville, Bala, and parts of the Antioch kimberlites contain the fewest xenoliths and, thus, have contamination indices (CI's) close to 1 (CI or contamination index = (SiO_2+Al_2O_3+Na_2O)/ (MgO+K_2O) as weight percent).

These least contaminated kimberlites are undersaturated in SiO_2 and contain low Na_2O/ K_2O ratios, Al_2O_3, K_2O, and Rb, and high LOI and TiO_2. These results confirm that these samples are kimberlites (Type I kimberlites) rather than orangites (Type II kimberlites). These kimberlites, like other kimberlites, also contain relatively high Cr, Ba, Sr, La, Ce, and $(La/Lu)_{cn}$ ratios compared to many other mantle-derived rocks. Plots of data relative to primitive mantle show anonymously low K and Rb concentrations relative to adjacent elements. These results are consistent with standard interpretations that type I kimberlites could be derived by small degrees of melting of a garnet-carbonate-phlogopite-peridotite or by larger degrees of melting of a varied mix of complex, carbonate-bearing veins and lherzolite-harzburgite.

Introduction

The kimberlites in Riley and Marshall counties, Kansas, were intruded during the late Cretaceous (K-Ar ages on phlogopite of 95±6 Ma and 112±-6 Ma) (Brookins, 1970b; Brookins and Naeser, 1971) as part of an over 4,000-km (2,484-mi) Cretaceous corridor of kimberlite occurrences (103–94 Ma) extending from northern Canada through the central USA (Heaman et al., 2004). The six originally discovered kimberlites [Bala, Leonardville, Randolph # 1 and #2, Stockdale, and Winkler (fig. 1 and table 1)] were studied by Brookins, Cullers, and students (Brookins, 1967, 1970a, b; Brookins and Naeser, 1971; Cullers et al., 1982). The first five of these six kimberlites are exposed at the surface. The Winkler kimberlite is not exposed at the surface, but its characteristic morphology in the form of a small crater, coupled with magnetic signature typical of kimberlites in the area, led to its discovery by drilling in 1969 (Brookins, 1970a).

Since these initial studies, there have been several exploration and digging-drilling campaigns resulting in seven additional kimberlite discoveries by Cominco American Inc. and the Kansas Geological Survey using stream-sediment sampling as well as aeromagnetic surveys followed by detailed ground magnetic surveys (Mansker et al., 1987; Berendsen and Weis, 2001). These kimberlites are the Lone Bush A and B, Lone Tree, Swede Creek, Antioch, Tuttle, and Baldwin Creek (fig. 1). The details of the most recently discovered kimberlites (Antioch, Tuttle, and Baldwin Creek) are presented in this paper. In addition, the petrography and chemical composition of all the kimberlites are discussed in terms of their relationship to each other and their petrogenesis.

History of Discovery

The Bala kimberlite (sec. 6, T. 9 S., R. 5 E.), so-called because of its proximity to the settlement of Bala, was discovered before 1919 by T. S. Harrison of Denver, Colorado (table 1). Moore and Haynes (1920) described the rock as an igneous breccia or agglomerate consisting of a groundmass of basalt and inclusions of shale in various stages of alteration. Calcite-filled fractures are common. The contact with the surrounding sedimentary rocks, assigned to the Permian Chase Group, is not exposed.

Physiographically the kimberlite was easily recognized because the rock forms a prominent northwest-protruding knoll some 20 ft (6 m) high above the creeks that surround the kimberlite on three sides.

The Leonardville kimberlite (sec. 22, T. 8 S., R. 5 E.) occurs about 1 mi (1.6 km) south of the town of Leonardville. Tolman and Landes (1939) credit A. B. Sperry with the discovery of the kimberlite sometime in 1934–35. The topographic expression of the kimberlite is minimal and consists of two small mounds on the west side of a gently sloping hill (Brookins, 1970b). The contact with Permian sedimentary rocks of the Chase Group is not exposed.

The Stockdale kimberlite (sec. 23, T. 8 S., R. 6 E.) was discovered in the late 1930's by Professor G. H. Failyer of Manhattan, Kansas. The rock is exposed in a creek bed and physiographically subdued. The contact with the surrounding

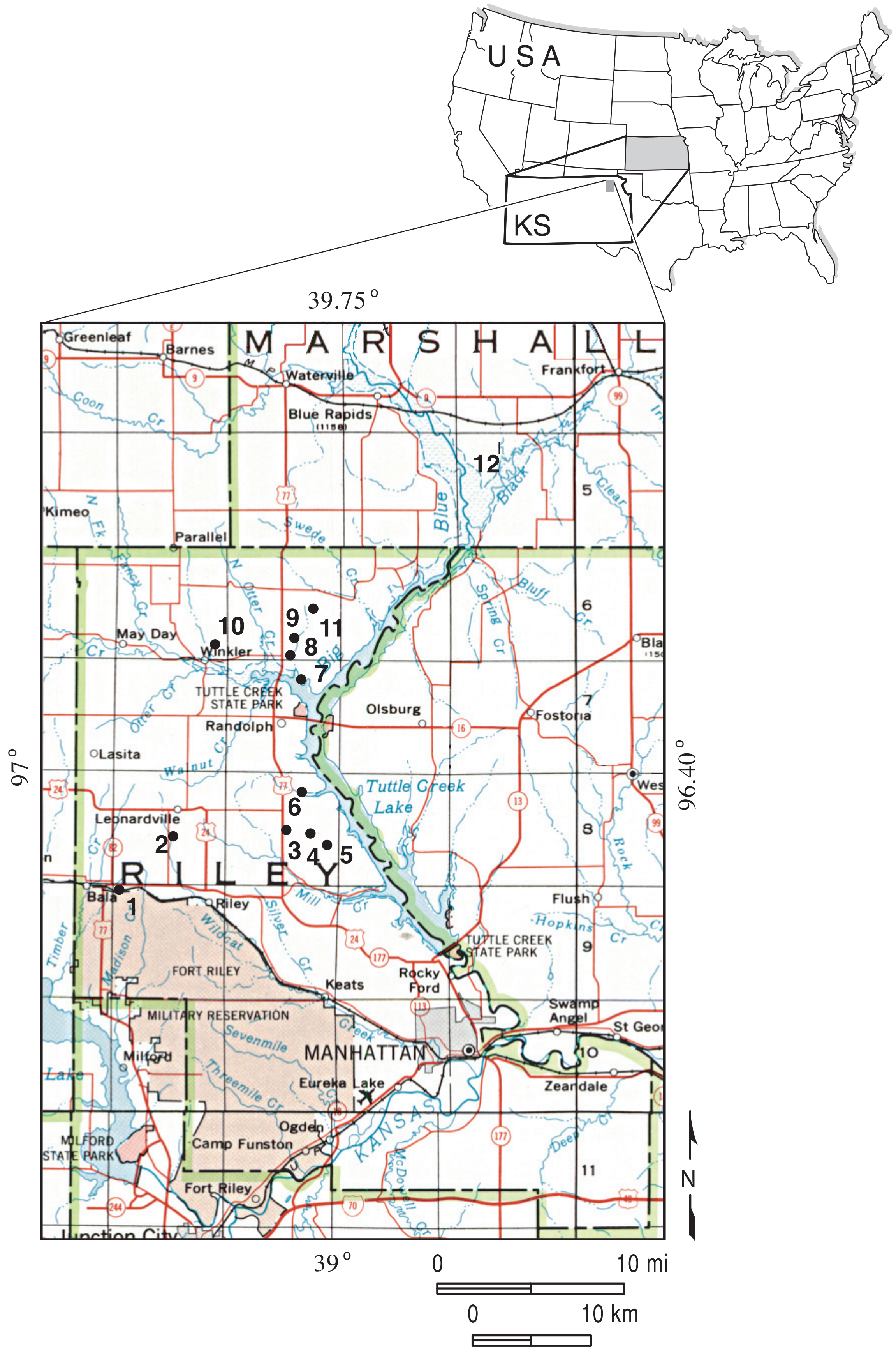

FIGURE 1—Kimberlite location map. See table 1 for names of kimberlites located on map.

TABLE 1—Kansas kimberlite locations and ground magnetic anomaly amplitudes and size.

Kimberlite	County	Latitude	Longitude	Amplitude	Size (acres)
1. Bala	Riley	N39°18'18"	W96°55'17"	>3500 nT*	>9.0*
2. Leonardville	Riley	N39°20'45"	W96°51'39"	2000 nT*	>8.0*
3. Tuttle	Riley	N39°20'52"	W96°45'00"	1600 nT	>1.2
4. Lonetree (a, b)	Riley	N39°20'39"	W96°43'48"	2168 nT*	2.8*
5. Stockdale	Riley	N39°20'30"	W96°43'26"	3000 nT*	6.0*
6. Baldwin Creek	Riley	N39°22'41"	W96°44'19"	900 nT	8.9
7. Fancy Creek	Riley	N39°28'23"	W96°44'01"	1066 nT*	9.5*
8. Randolph #1	Riley	N39°29'19"	W96°44'01"	6321 nT*	0.9*
9. Randolph #2	Riley	N39°29'43"	W96°44'30"	–	–
10. Winkler	Riley	N39°29'24"	W96°49'13"	500 nT*	18.5*
11. Swede Creek	Riley	N39°31'01"	W96°43'00"	5794 nT*	0.8*
12. Antioch	Marshall	N39°38'14"	W96°32'03"	1200 nT	>1.3

*From Mansker et al., 1987.

sedimentary rocks, assigned to the Permian Chase Group, is not exposed. The rock was described by Jewett (1941) as an igneous breccia or an agglomerate, consisting of a groundmass of dark-green material containing numerous inclusions of sedimentary rock in various stages of alteration (fig. 2). The inclusions consist of shale, flint, and limestone. Another interesting feature is that the rock contains many crystals of small, badly shattered, wine-colored garnets.

K. L. Parish recognized two other intrusions in Riley County to be of igneous origin in 1950 (Byrne et al., 1956). These kimberlites occur within close proximity to each other. The Randolph #1 (sec. 35, T. 6 S., R. 6 E.) forms a circular hill, about 200 ft (61 m) in diameter, and rises about 10 ft (3 m) above the surrounding area. On the west and northeast side, Permian shale of the Chase Group dips away from the intrusion. The rock consists of a fine-grained matrix of serpentinized and calcitized olivine containing numerous altered sedimentary and igneous inclusions.

About one-half mile (0.8 km) to the northwest of the Randolph #1 kimberlite another kimberlite, the Randolph #2 (sec. 27, T. 6 S., R. 6 E.), is exposed at the surface. This kimberlite forms a low (3–4 ft [0.9–1.2-m] high) circular hill on the generally eastward-dipping slope. The contact with the Permian sedimentary country rocks of the Chase Group is not exposed. This kimberlite does not have the characteristic light-gray-blue-greenish color of most kimberlites. The rock is a much darker greenish-gray, having a very fine grained matrix and few inclusions. Carbonate veinlets are common.

The sixth kimberlite, Winkler, does not crop out at the surface but was discovered by drilling in 1969 (Brookins, 1970a). The Winkler kimberlite is a circular, 950-ft (290-m)-diameter topographic low that is easily recognized on topographic maps and aerial photographs (fig. 3). This feature is also referred to as the Winkler crater and was earlier thought to be a meteorite crater (Barringer, 1964; Freeberg, 1966). Drilling in 1969 (Brookins, 1970a), and trenching by Cominco American, Inc. in 1985 (fig. 4) proved beyond doubt that Winkler is a kimberlite .

For the next 20 years there was little interest in the kimberlites. However, with renewed worldwide interest in diamond exploration and the discovery of several new diamondiferous deposits in Australia and Canada, exploration for and evaluation of kimberlites and lamproites in North America also increased dramatically. One of the companies that played a prominent role in this process was Cominco American Inc. In the early 1980's, Cominco evaluated most of the known and newly discovered kimberlites and lamproites occurring on the stable craton in the continental U.S.A. During the time period from 1980 to 1984, the company conducted exploration in northeast Kansas. Exploration methods included alluvial sampling, low-altitude color infrared aerial photography, and airborne magnetic surveys. The exploration efforts identified four new kimberlites and three potential kimberlites based upon interpretation of magnetic data. The four new kimberlites discovered as a result of this activity were named: Lonetree A, Lonetree B, Fancy Creek, and Swede Creek (fig. 1, table 1).

Aeromagnetic data clearly showed a number of anomalies, including three anomalies that Cominco American Inc. considered to be potential kimberlites (Weis and Berendsen, 2000). The Kansas Geological Survey conducted detailed ground magnetic surveys and followed it up by drilling and coring each of the three anomalies, resulting in the discovery of the Baldwin Creek, Tuttle, and Antioch kimberlites.

The Baldwin Creek kimberlite (fig. 1) in Riley County occurs in the east-west-trending Baldwin Creek drainage, which empties in Tuttle Lake to the east. This kimberlite is not exposed on the surface and occurs beneath approximately 29 ft (8.8 m) of alluvium. The kimberlite was drilled and cored to a depth of 308 ft (94 m).

The Tuttle kimberlite is located about 3 km (1.87 mi) southwest of the Baldwin Creek kimberlite (fig. 1) and a little over 1.6 km (1 mi) west-northwest of the Stockdale and Lone tree A and B kimberlites. This kimberlite is very close to the surface. Garnets and ilmenite are widely distributed on the surface. The kimberlite was drilled and cored to a depth of 307 ft (94 m).

The Antioch kimberlite is located in south-central Marshall County (fig. 1). The kimberlite is not exposed at the surface and is covered by about 20 ft (6 m) of alluvial material. The kimberlite was drilled and cored to a depth of 308 ft (94 m).

Trenching and bulk sampling of seven known and newly discovered kimberlites revealed that, with the exception of one kimberlite, all others did not yield any diamonds. The Fancy Creek kimberlite yielded two microdiamonds (5.2 and 16.4 mg each respectively (Cominco American Resources

FIGURE 2 (left)—An exploration trench dug by Cominco American Inc. in 1985, exposing the Stockdale kimberlite. Looking west.

FIGURE 3—High-altitude infrared photograph showing the Winkler kimberlite.

FIGURE 4—Winkler kimberlite looking east from the west rim of the crater and showing exploration trenches dug in 1985 by Cominco American Inc.

Incorporated, 1993). However these findings were attributed to likely contamination from other sources (G. P. Cole, personal communication).

Information obtained during this phase of exploration was donated to the Kansas Geological Survey by Cominco American Inc. in 1999 with the disclaimer that all interpretive work published by the Kansas Geological Survey is a product of the Kansas Geological Survey and that Cominco American Inc. has had no involvement in developing these interpretations.

Geology

General Geology

All kimberlites occur geographically over the trace of the Central North American Rift System (CNARS) in Riley and Marshall counties (fig. 5) in northeastern Kansas (Berendsen and Blair, 1986). Mansker et al. (1987) state that kimberlites are situated along the southeast flank of the Abilene anticline–Irving syncline, both geologic structures defined by Jewett (1951) in the same general area.

The basement rocks making up the CNARS are 1.1-b.y.-old Proterozoic basic flows and intrusives as well as slightly younger, mostly arkosic sedimentary rocks filling in the rift basin (Cullers and Berenden, 1993). Sedimentary rocks up to 2,625 ft (800 m) thick, and ranging in age from Ordovician to Permian, occur over the Proterozoic basement rocks.

In the immediate vicinity of the kimberlites, exposed Permian sedimentary rocks consisting of shale and limestone/dolomite are commonly folded and faulted. Faults in the area are subtle features showing little displacement. Small-scale (about 3 ft [1 m]) normal and reverse faults are apparent in several road cuts throughout the area. Because the timing of the faults is difficult, if not impossible to establish, they may be related to the emplacement of the kimberlites or the result of periodic tectonism. Another cause of small-scale faulting and folding may be dissolution of salt in the shallow subsurface that has caused intraformational deformation in the area (Berendsen et al., 1998). Whether the faulting is a direct result of the intrusive activity cannot be established, because the whole area overlying the Midcontinent Rift System (MRS) has experienced repeated tectonic activity throughout time.

The kimberlites are stratigraphically late Cretaceous in age (Mansker et al., 1987) intruding limestones and shales of the Chase Group, and contain xenoliths of the same age. Cretaceous and younger xenoliths have not been identified in any of the kimberlites (Mansker et al., 1987). Brookins (1970), who studied the kimberlites in detail, reports K-Ar pre-emplacement dates ranging from 95±6 m.y. to 380±40 m.y. determined on highly altered phlogopite. The younger age has in general been given

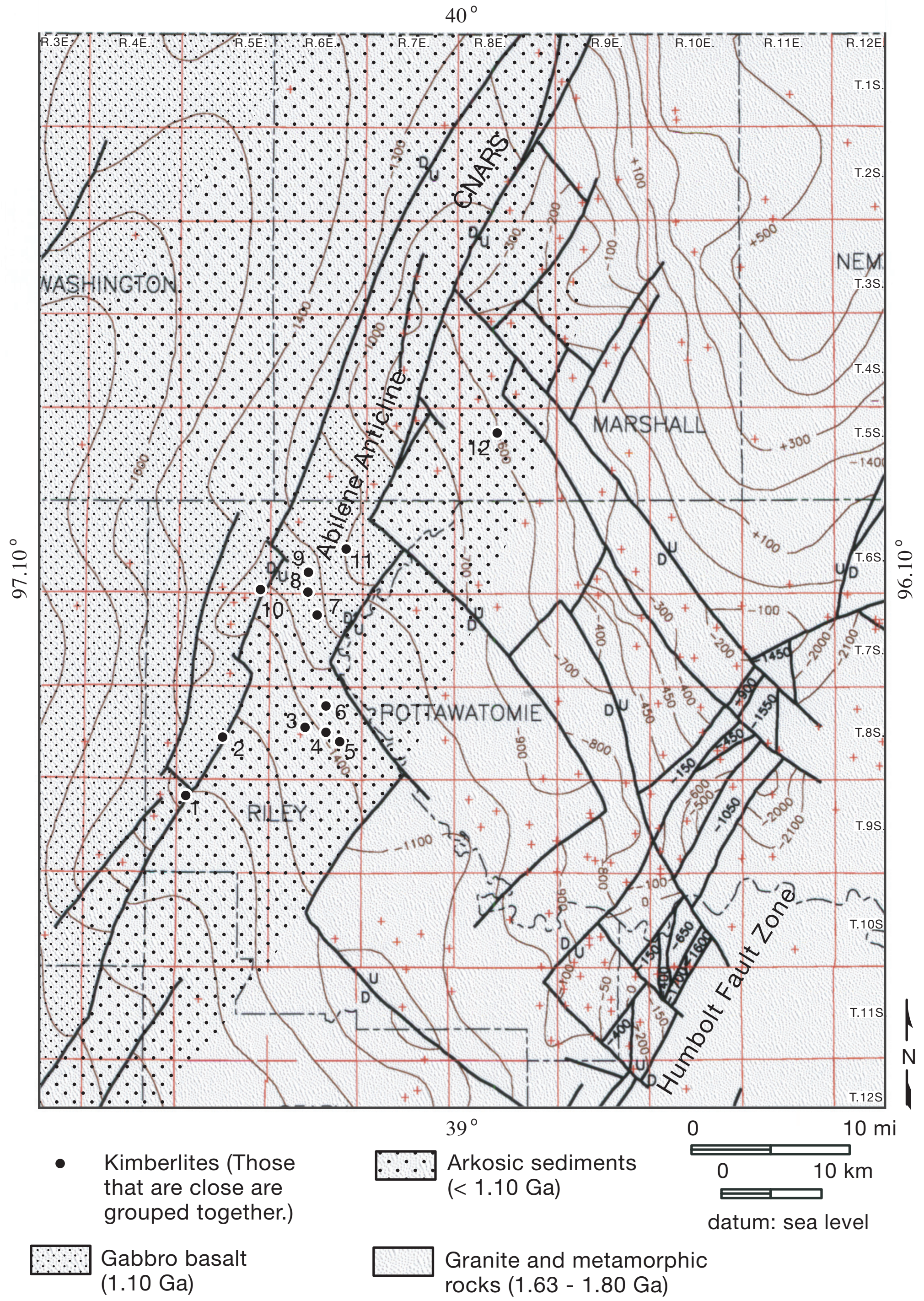

FIGURE 5—Map of Precambrian structure and lithology, showing the location of kimberlites.

more credibility because similar intrusives in the midcontinent, particularly the lamproite intrusives in Woodson County (Zartman et al., 1967), were dated at approximately 90 m.y. More recent studies using (U/Th)/He dating techniques on apatite and titanite (Blackburn et al., 2004) from the Stockdale, Tuttle, and Leonardville kimberlites give reproducible ages between 61 and 68 Ma.

The Leonardville, Stockdale, and probably Winkler kimberlites, were originally classified as micaceous kimberlites due to their high phlogopite content, whereas the Bala, Randolph #1, and Randolph #2 were originally classified as lamprophyric kimberlites, because of their deficiency of phlogopite (Brookins, 1970b).

Texturally the kimberlites range from crater to diatreme facies in Riley County to possible hypabyssal facies in Marshall County.

Field relations, hand specimen descriptions and petrographic observations of the Fancy Creek, Lone Tree, and Swede Creek kimberlites have been reported in a previous study (Mansker et al., 1987). The Fancy Creek kimberlite was classified as a tuffaceous, crater facies, the Lone Tree A as a diatreme facies, and the Swede Creek as a hypabyssal facies. The Fancy Creek was intruded into the Barnston Limestone (Mansker et al., 1987). The Lone Tree and the Swede Creek were covered by glacial alluvium (Mansker et al., 1987).

The Antioch, Tuttle, and Baldwin Creek kimberlites are not exposed at the surface, but are buried under a shallow soil cover up to 26 ft (8 m) thick. Permian age rocks form the bedrock at all three kimberlites. The Blue Springs Shale Member of the Matfield Shale constitutes the bedrock at the Baldwin Creek kimberlite, and the Odell Shale is the bedrock at the Tuttle kimberlite. Because the Antioch kimberlite occurs in an area of unconsolidated Quaternary material, the nature of the bedrock is unknown.

Structure

Information obtained from hundreds of holes drilled within the general vicinity of the rift were used to construct interpretive structure contour maps on top of major Paleozoic formations and the top of the Precambrian basement (fig. 5). Analyses of such maps allow us to identify major faults and fault trends in the subsurface. Reactivation involving major movement along several of these structures can be demonstrated to have occurred throughout geologic time. North-northeast-trending, rift-related structures are prevalent. All the kimberlites are closely associated with the trend of the axial portion of the rift, which is locally recognizable as an anticlinal fold in Permian surface rocks and known as the Abilene anticline (Jewett, 1951). East of the axial portion of the rift, a North-northeast-trending zone of complex faulting constitutes the well-known structural element referred to as the Humboldt Fault Zone (fig. 3). In most places, the Humboldt Fault Zone consists of a number of anastomosing stepped-down-to-the-east, high-angle normal and reverse faults, showing compound vertical displacement in excess of 3,000 ft (915 m). Older, regularly spaced northwest-trending faults of regional significance also are prominent and break the area up into orthogonal blocks (Sims and Peterman, 1986). The lateral component of movement on these faults is likely greater than the vertical displacement (Clendenin et al., 1989). Several of the kimberlite bodies show a more or less circular outline (e.g. Winkler), while others display a distinct southeast-northwest elongation (Baldwin Creek, Tuttle, Antioch, Stockdale, and Lonetree).

Geophysical Surveys

General Information

Dreyer (1947) conducted a magnetic survey over the Bala kimberlite. He interprets the kimberlite mass to be an eastward-plunging vertical dike-like body trending N. 69° W.

The Leonardville kimberlite is a northwest-trending vertical or steeply dipping dike more than 1,700 ft (518.5 m) long and 500 ft (152.5 m) wide as indicated by a magnetic survey (Cook, 1955). A shallow saddle separates the narrow southeastern part from the wide, shallow, bifurcating northern part (Cook, 1955).

According to Cook (1955) the Stockdale kimberlite is a parallelepiped body plunging south-southeast. It is about 200 ft (61 m) across and just below the land surface.

A magnetic survey conducted at the Randolph #1 kimberlite indicates a truncated cylindrical or prismatic body plunging to the south-southeast. The dimensions of the body are 220 ft (67 m) east-west by 180 ft (55 m) north-south and it is close to the surface (Cook, 1955)

A similar magnetic survey over the Randolph #2 kimberlite shows it to be a finger-like pipe plunging south-southeast. The body is elliptical in cross section, 60 ft (18 m) east-west by 40 ft (12 m) north-south (Cook, 1955).

High-resolution ground-penetrating radar (GPR) was used to image the near surface extent of the Randolph #1 and Randolph #2 kimberlites in Riley County (Kruger et al., 1995, 1997). The up-bending and termination of limestone reflectors seen on six parallel GPR profiles identify the margins of the Randolph #1 kimberlite. The elliptical margin of the Randolph #2 kimberlite is evident on five radially intersecting profiles that show the termination of dolomite reflectors near or below the kimberlite's mushroom-shaped cap. GPR studies may provide additional useful information about the near-surface configuration of kimberlites and other intrusions where conductive shale or soil is absent or thin at the surface (Kruger et al., 1997).

Aeromagnetic data (line spacing of 200-400 m) covering three tracts of land in Riley and Marshall counties were donated to the Kansas Geological Survey by Cominco American, Inc. in 1999 (fig. 1). Examination of the aeromagnetic data outlined a number of potential kimberlite targets. Reconnaissance ground magnetic surveys indicated that three of the targets (Antioch, Tuttle, and Baldwin Creek anomalies) exhibited the characteristic signature of a kimberlite (magnetic contrast, amplitude, and size). Detailed ground magnetic surveys were utilized to locate the selected aeromagnetic anomalies on the ground, to map their shapes, and to locate test drill holes to test the sources of the anomalies. Preliminary reconnaissance lines, aeromagnetic maps (1:24,000 scale) donated by Cominco American Inc., aeromagnetic interpretation maps (1:48,000 scale) (Weis and Berendsen, 2000), topographic maps, and GPS were used for this purpose. After the anomalies were located, detailed grids were established using chain and compass. The line spacing was 15 and 30 meters; station spacing was 5 meters. The line directions for the Antioch, Tuttle, and Winkler grids are north-south. The Baldwin Creek grid is rotated 20° east of north. All data discussed in this presentation were collected using a Geometrics G-856 proton precession memory magnetometer system. This included a base magnetometer for applying diurnal corrections.

The data sets were modeled using the GM-SYS™ gravity and magnetic modeling package. The resulting 2.5-D models were used to define targets for drilling and coring.

Antioch Kimberlite

Multiple small magnetic bodies are identified by the ground magnetic survey at Antioch. The main anomaly is a large-amplitude, 1200-nanotesla (nT), circular anomaly with a diameter of approximately 30 m (98 ft) (fig. 6). It is colored red in the fig. 6 and occurs at approximately the center of the grid. This target was drilled and a kimberlite was intersected at a depth of approximately 20 ft (6 m). Susceptibility logging of the core revealed that this kimberlite is an order of magnitude more magnetic than the other kimberlite bodies discussed in this presentation (fig. 7). The Antioch kimberlite is a more complex

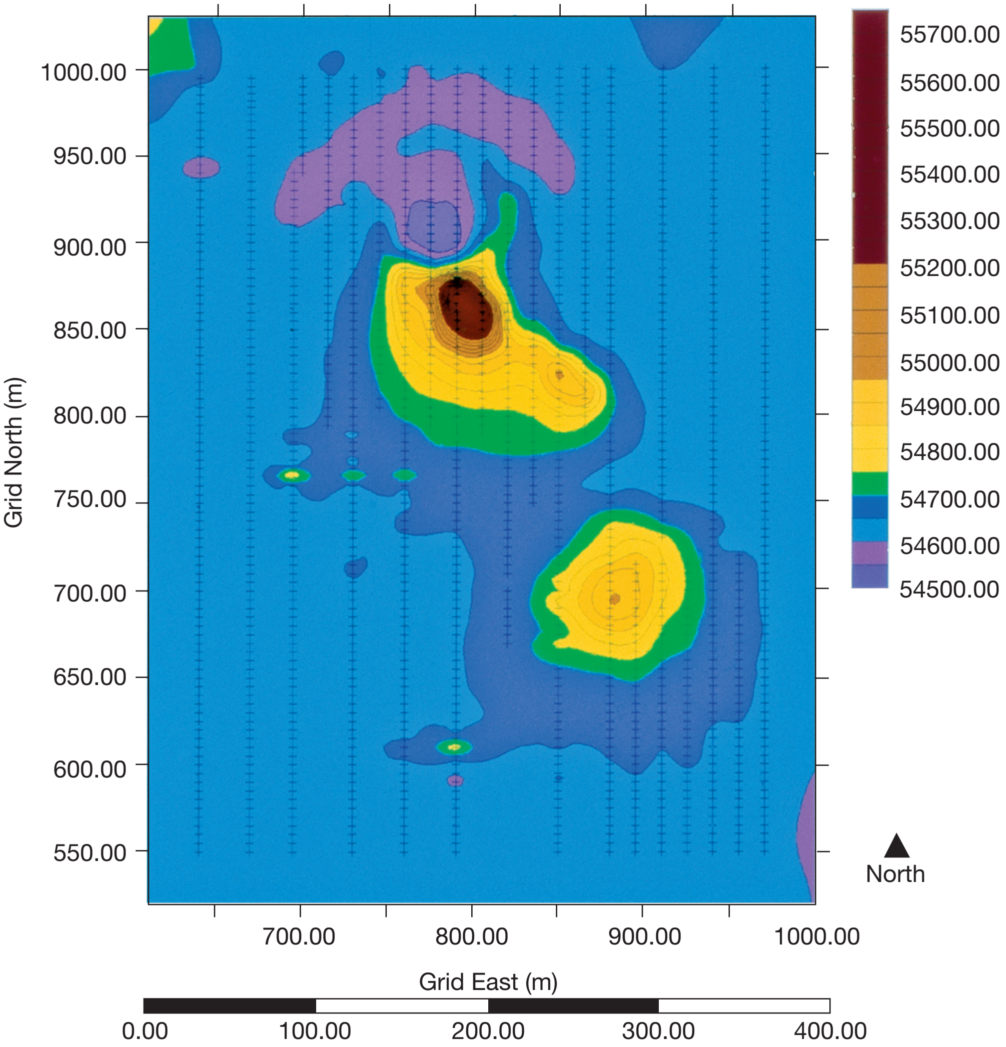

FIGURE 6—Antioch ground magnetic anomaly, Marshall County, Kansas.

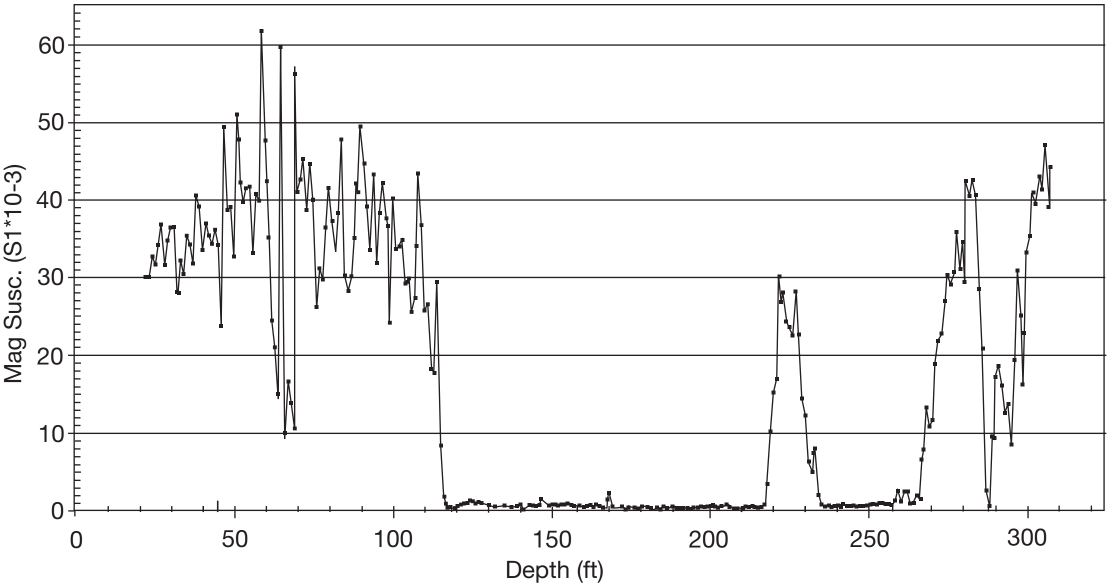

FIGURE 7—Antioch magnetic susceptibility plot.

occurrence and probably represents two distinct kimberlite intrusions approximately 150 m (492 ft) apart. The northern anomaly is a composite anomaly consisting of a small-diameter circular anomaly with a maximum amplitude of approximately 1200nT. A northwest-trending elongate dike-like anomaly extends to the southeast and northwest of the circular anomaly. A circular magnetic low surrounded by a dike-like high occurs at the northern edge of the anomaly complex (fig. 6). A second circular anomaly is located approximately 200 m (656 ft) to the southeast of the main anomaly. It is interpreted to be a kimberlite but remains untested. Modeling of the northern composite anomaly indicates a steeply dipping pipe-like intrusion located within 10 m (33 ft) of the surface (fig. 8). Modeling of the southern circular magnetic anomaly indicates it is a composite body having at least two small, steeply dipping sources (fig. 8). The modeled depth to the top of the kimberlite is about 20 m (66 ft).

Baldwin Creek Kimberlite

Preliminary ground magnetic survey work carried out at Baldwin Creek in the 1980's indicated that a kimberlite was present at that locality (Mansker et al., 1987). The 1999 detailed ground magnetic survey (Berendsen and Weis, 2001) indicated that the anomaly had a maximum amplitude of approximately 900 nT and a northwest-trending body in the subsurface (fig. 9). Modeling of the data indicated that the kimberlite was a steeply dipping, structurally controlled intrusive (fig. 10) bound on the southwestern side by a northwest-trending fault along which the kimberlite probably intruded. The location, ground magnetic amplitudes, and approximate size of the 12 known kimberlites are shown in table 1.

A large, 250 x 150 m (820 x 492 ft) magnetic anomaly was identified by ground magnetic data at Baldwin Creek. The long axis of the anomaly strikes approximately 320° azimuth and appears to be structurally controlled. The peak anomaly amplitude is 1000 nT. A drill hole was located on the anomaly peak at the southeast edge of the anomaly and intersected a kimberlite at approximately 25 ft (7.6 m) depth. The magnetic susceptibility (fig. 11) is less then the Antioch kimberlite susceptibility; however, due to the large size of the Baldwin Creek kimberlite the resulting magnetic anomaly amplitude is similar.

Tuttle Kimberlite

The Tuttle magnetic anomaly is only partially defined due to the close proximity of a home and outbuildings (fig. 12). The anomaly is circular and approximately 60 m (197 ft) in diameter (fig. 13). The maximum anomaly amplitude is approximately 1200 nT. The anomaly was drilled at the peak and indications of weathered kimberlite were detected within a couple feet of the surface. Indicator minerals are easily found on the surface, giving credence to the hypothesis that the kimberlite might be slightly

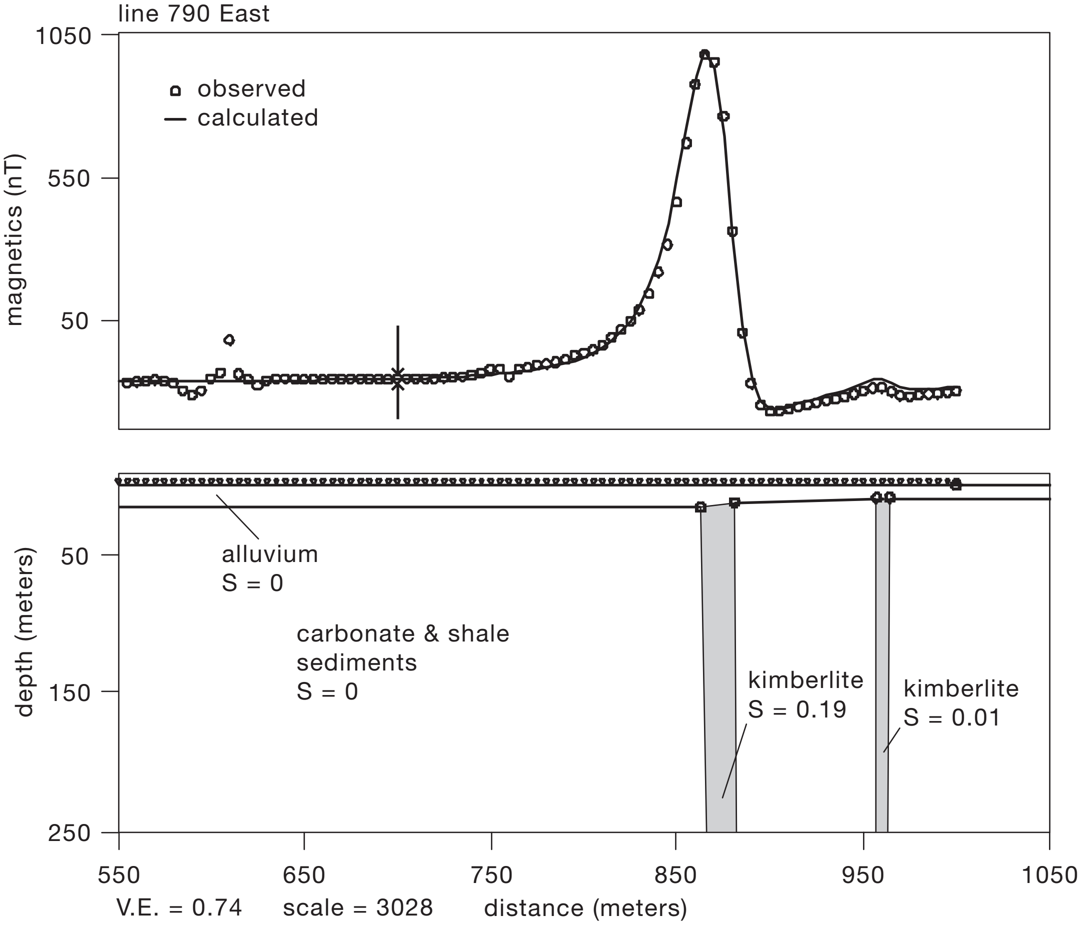

FIGURE 8—2.5-dimensional magnetic model of the Antioch kimberlite.

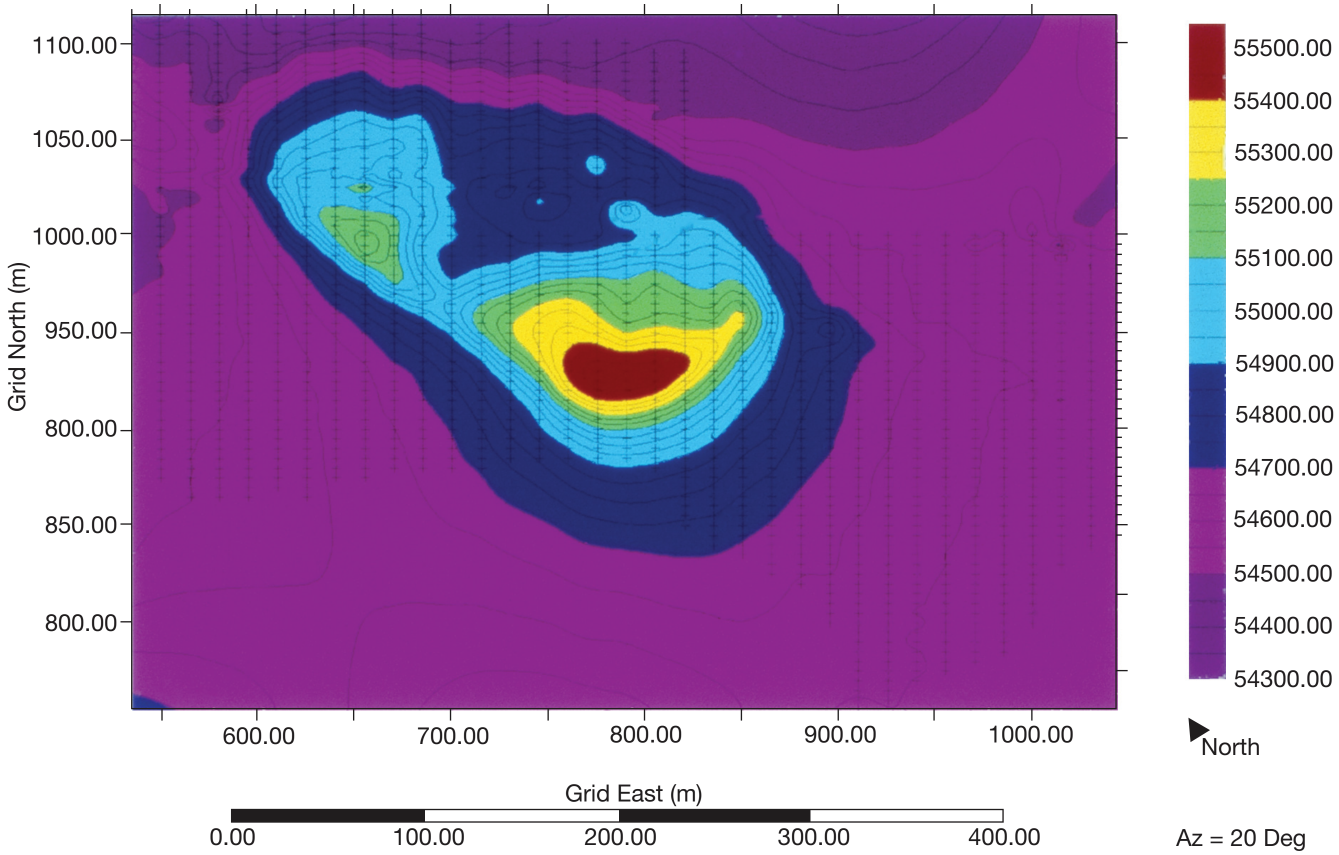

FIGURE 9—Baldwin Creek ground magnetic anomaly, Riley County, Kansas.

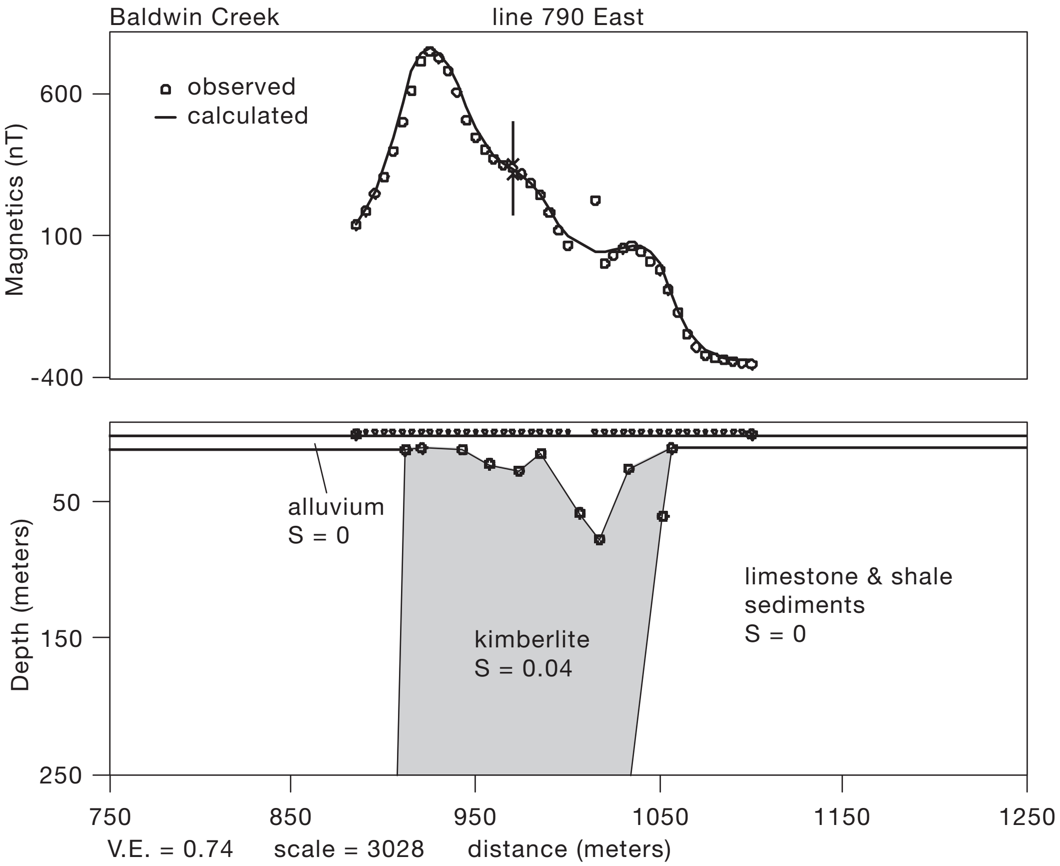

FIGURE 10—2.5-dimensional magnetic model of the Baldwin Creek kimberlite.

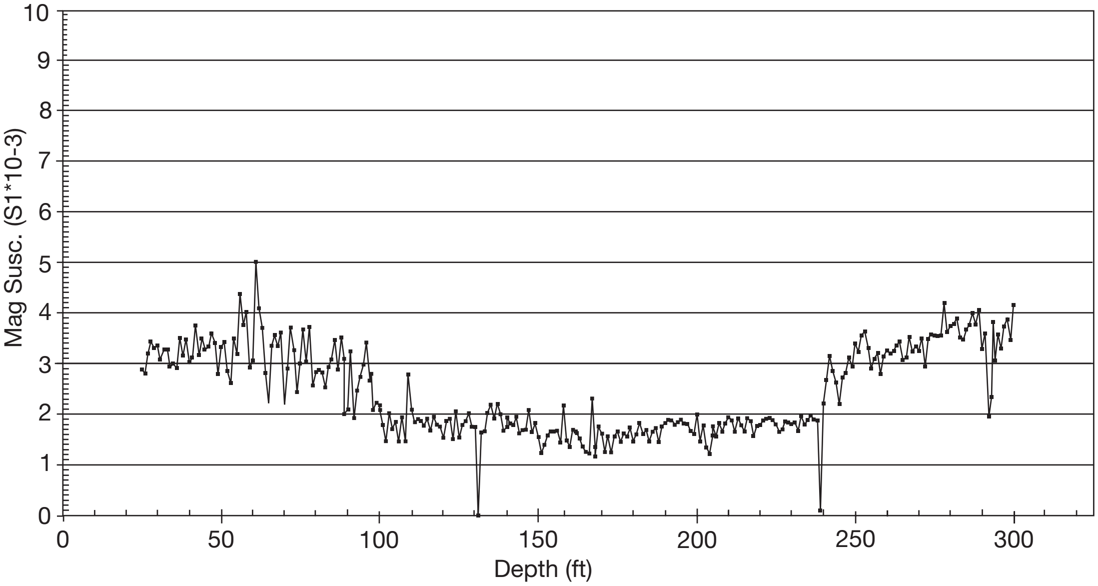

FIGURE 11—Baldwin Creek magnetic susceptibility plot.

elongated in a northwesterly direction. The shallow depth of the Tuttle kimberlite causes the large magnetic anomaly amplitude. The magnetic susceptibility of the Tuttle kimberlite is similar to the Baldwin Creek kimberlite (fig. 14). Modeling of the limited data set indicates that the kimberlite body is steeply dipping (fig. 15).

Winkler Kimberlite

The Winkler kimberlite was discovered in the 1960's and is clearly visible on high-altitude infrared color imagery (fig. 3). A detailed ground magnetic survey was run over the kimberlite to map its shape and explore for dike-like bodies adjacent to the kimberlite (fig. 16). The kimberlite is circular with a diameter of approximately 300 m (984 ft). The maximum anomaly peak is approximately 800 nT. No additional kimberlite dikes were located adjacent to the main kimberlite body. Winkler was drilled in the early 1980's; no core or magnetic susceptibility measurements are available.

FIGURE 12—Aerial photograph of the Tuttle kimberlite. The approximate outline of the kimberlite is indicated by the black dotted line.

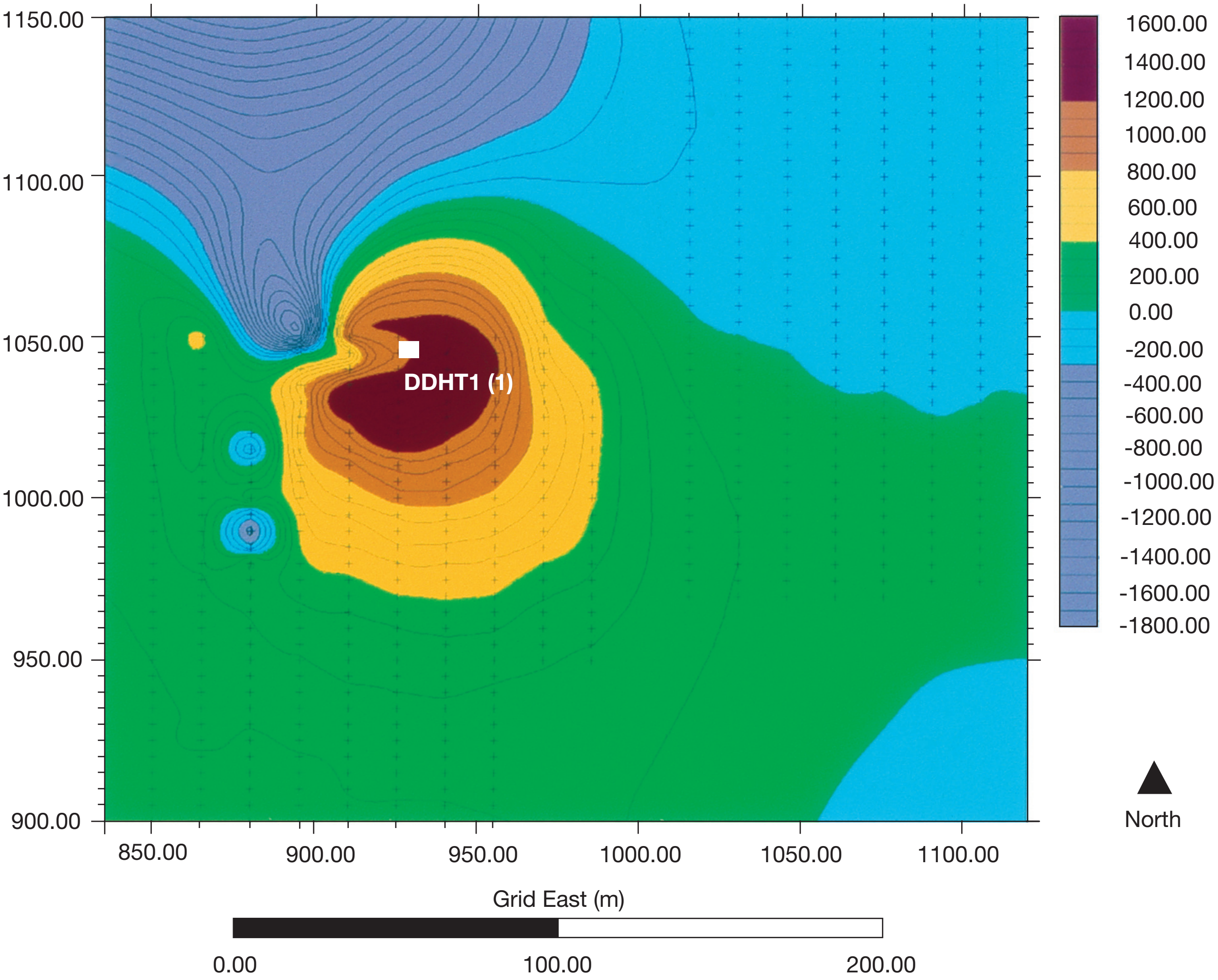

FIGURE 13—Tuttle ground magnetic anomaly, Riley County, Kansas.

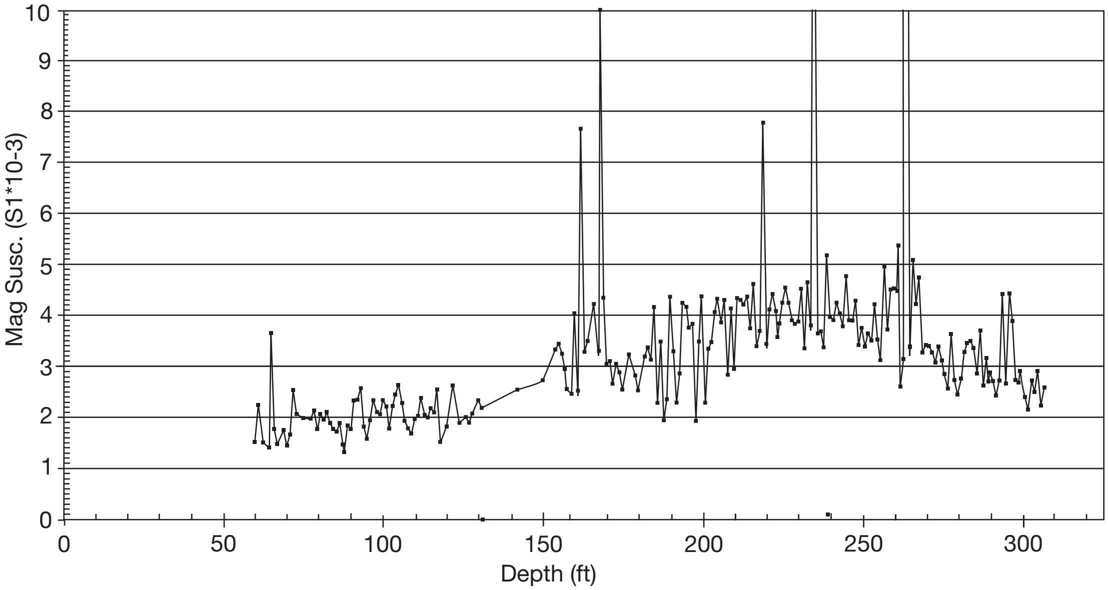

FIGURE 14—Tuttle Magnetic susceptibility plot.

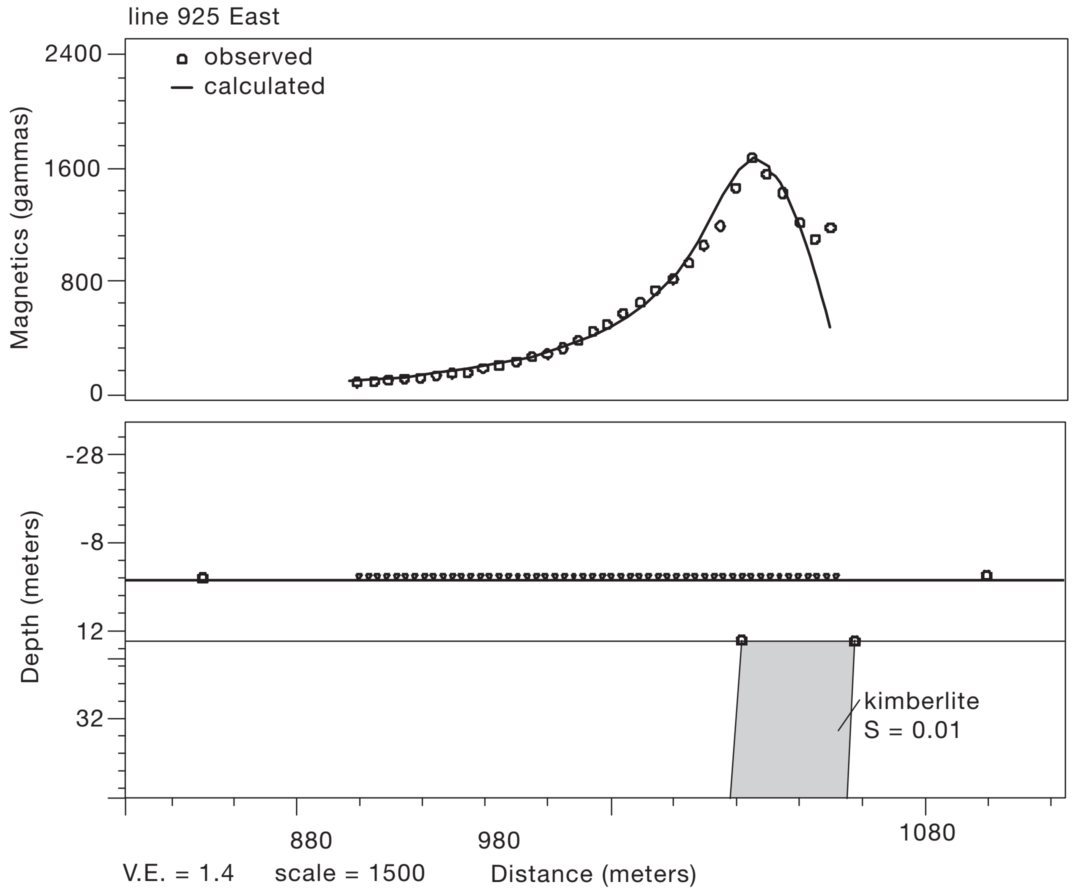

FIGURE 15—2.5-dimensional magnetic model of the Tuttle kimberlite.

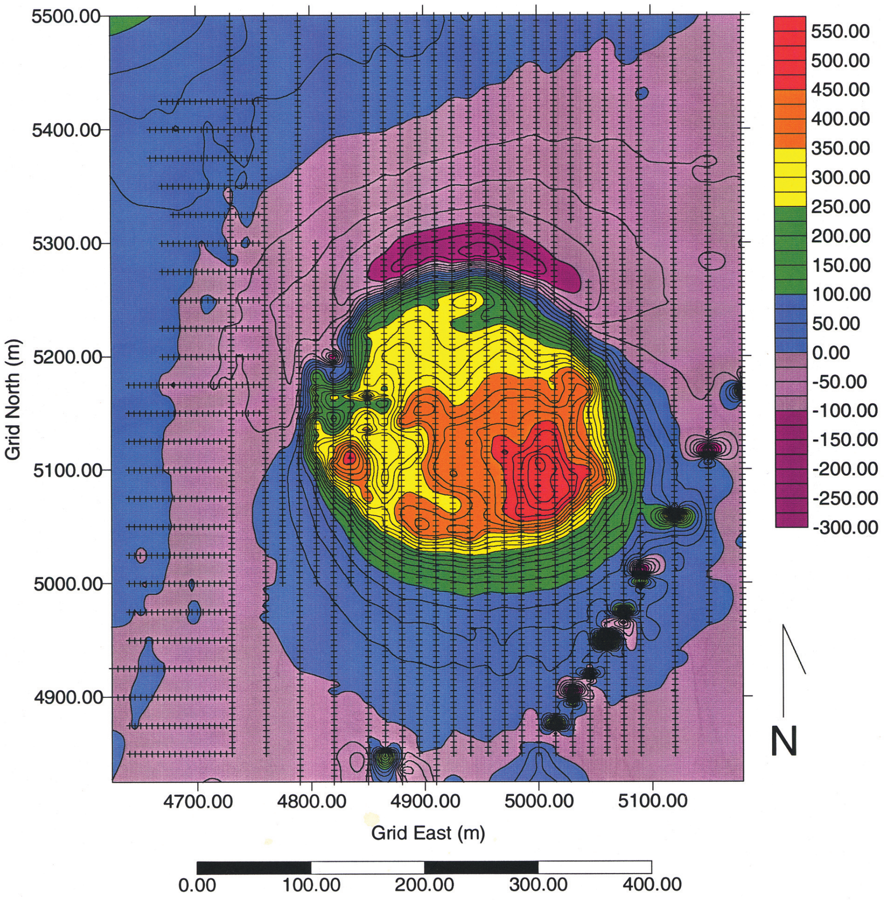

FIGURE 16—Winkler kimberlite ground magnetic anomaly, Riley County, Kansas.

Lithology and Petrography

Previous Studies

More than 90% of the Bala, Leonardville, Randolph #1 and #2, Stockdale, and Winkler kimberlites consist of serpentine and calcite and all but Randolph #2 are crowded with mostly crustal xenoliths (Brookins, 1970). The xenoliths are mostly limestone or shale and minor basalt, granite, and arkose. The minerals of the kimberlites are serpentinized forsterite-rich olivine, serpentinized clino- and orthopyroxenes, ilmenite, magnetite, apatite, perovskite, and carbonate (Brookins, 1970). In addition, some contain chloritized phlogopite (Leondardville, Stockdale, and Winkler), pyrope, and melilite (Brookins, 1970).

The Swede Creek kimberlite contains abundant serpentinized-carbonatized pseudomorphs after olivine with lesser magnetite, ilmenite, phlogopite, apatite, pyrope garnet, ilmenite, and chrome diopside (Mansker et al., 1987). In this respect, it is most similar in mineralogy to the Bala and Randolph #1 and #2 kimberlites. A network of carbonate veins permeate the samples.

The Fancy Creek kimberlite is brecciated and in that respect is much like the Winkler kimberlite (Mansker et al., 1987). Rock fragments are abundant and are mostly sedimentary with minor granite, diorite, and garnet peridotite (Mansker et al., 1987). The Fancy Creek consists of serpentinized-carbonatized olivine, and lesser pyrope garnet, chrome diopside, ilmenite, and phlogopite (Mansker et al., 1987).

The Lone Tree kimberlite is most similar to the mineralogy of the Stockdale kimberlite except that magnetite is in lower abundance (Mansker et al., 1987). They contain abundant xenoliths with similar minerals in a brecciated matrix (Mansker et al., 1987).

Antioch Kimberlite

The lithology of the Antioch kimberlite in Marshall County is quite different from the other two occurrences as well as the other known kimberlites (appendix A). The kimberlite, down to a depth of 115 ft (35 m), is hard and has a dark-gray-green color. The matrix is very fine grained and contains many small xenoliths that cannot be identified in hand specimens. The rock is pervasively fractured, with the fractures being partially or completely filled by secondary calcite (fig. 17). Small dark-red patches in the upper 98 ft (30 m) are related to the fractures and believed to result from oxidation of iron-rich minerals to iron oxide (fig. 18). No garnet, ilmenite, or other major mineral constituents can be recognized in the core. From 115 to 220 ft (35–67 m) the rock changes to a lighter-gray-green, less-competent kimberlite, having larger and more numerous, as well as less metasomatised, xenoliths. Below this depth the kimberlite changes abruptly to the same dark-gray-green, very fine grained rock above. Then from 233 to 266 ft (71–81 m), another sharp change to the lighter-colored, less-competent kimberlite occurs. The last 43 ft (13 m) is again a dark-gray-green-colored competent kimberlite. From hand specimen examination it is difficult to tentatively classify this kimberlite. The core contains segments of kimberlite one tends to relate to the diatreme facies, but on the other hand it also contains segments that may be more indicative of the hypabyssal facies. The rock in the core may be a good example of multiple pulses of intrusion of kimberlitic material.

Hand specimen examination shows that different kinds of kimberlitic material occur in the Antioch kimberlite. Thin section examination (Appendix B) shows that the sections of the core that consist of the lighter-colored material with numerous xenoliths are tuffisitic kimberlite, having a texture similar to that of the Tuttle kimberlite, and can be described as inequigranular, pseudo-conglomeritic to pseudo-sandy, massive and unoriented. The groundmass, which occupies from 20 to 30% by volume, consists of a mixture of very fine grained serpentine minerals. Minor micas, opaque minerals and abundant secondary calcite also occur (appendix B).

Phenocrysts are generally quite rare, except in a section at 234 ft 9 inches, where they make up about 20% of the volume of the rock. They consist primarily of idiomorphic serpentine pseudomorphs after olivine, and opaque minerals commonly rim them. Many serpentine pseudomorphs after olivine are partially or wholly replaced by secondary fine- to medium-grained calcite.

Xenoliths are very common and make up to 80% of the rock volume. Xenoliths of different kimberlites are rare to ubiquitous and consist of peridotite-dunite, as well as dark-green-colored lamprophyre (micaceous). They are spheroidal and oval in shape and range in size from 1 to 10 mm. Country-rock xenoliths are again quite common and consist mostly of limestone and shale fragments that may be quite large.

The gray-green, dark-colored, very fine grained rock is a hypabyssal kimberlite. The texture of the rock is quite homogeneous, fine- to medium-grained, porphyritic, massive, and unoriented, typical for highly altered volcanic or subvolcanic

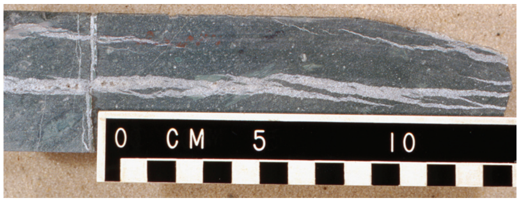

FIGURE 17—Antioch kimberlite at 52 ft. Kimberlite is very fine grained and cut by random oriented calcite-filled fractures.

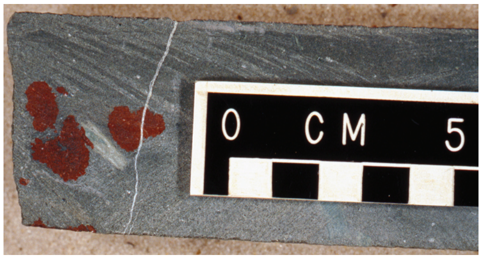

FIGURE 18—Antioch kimberlite at 38 ft 9 inches. Red, iron oxide patches.

rocks. The groundmass makes up most of the volume of the rock and consists of very fine grained serpentine minerals, micas, opaque minerals, and secondary calcite crystals and/or nests. The opaque minerals are usually much smaller than the serpentine pseudomorphs.

Micro-phenocrysts are common and consist mostly of colorless, fine-grained serpentine pseudomorphs after olivine. Many are rimmed by opaque minerals and sometimes by very fine grained serpentine.

Xenoliths are not common and are mainly small, rounded kimberlite. They have a fine-grained groundmass with minute microcrysts of mica and serpentine. Most contain abundant calcite, and they have a thin micritic rim.

Another, less common phase, consisting of ash (pelitic tuff) is present in the Antioch kimberlite at a depth of 288 ft 2 inches (88 m). The texture of the rock is quite homogeneous, fine grained (pelitic), locally having medium-grained (aleuritic) spots, massive, and unoriented. The groundmass, making up most of the rock, is a very fine grained, pelitic material, which is difficult to identify under the polarizing microscope. The detrital fraction consists of abundant aleuritic grains (muddy fraction) in which colorless micas, other phyllosilicates, K-feldspar, and plagioclase are recognized. This rock occurs over an interval of about 1 ft (0.3 m), and may represent a large xenolith.

Baldwin Creek Kimberlite

Down to a depth of 115 ft (35 m) the kimberlite is weathered and easily breaks apart (Appendix C). Numerous small cavities up to 1 inch (2.5 cm), some lined with calcite, are common. Below this depth, the kimberlite gradually takes on a darker gray-green color and contains many gypsum-filled fractures. The rock contains numerous angular to rounded Paleozoic xenoliths of sedimentary origin, mostly limestone and shale, and lesser amounts of generally smaller, metasomatized basement and crustal fragments (fig. 19). Millimeter-size garnets (fig. 20) and ilmenite are scattered throughout, as are larger clusters of mica, which is believed to be phlogopite. The kimberlite is a micaceous variety and is tentatively classified as diatreme facies. The number and type of xenoliths is similar to that in the Tuttle kimberlite.

FIGURE 19—Baldwin Creek kimberlite at 256 ft. Many xenoliths and a gypsum-filled fracture.

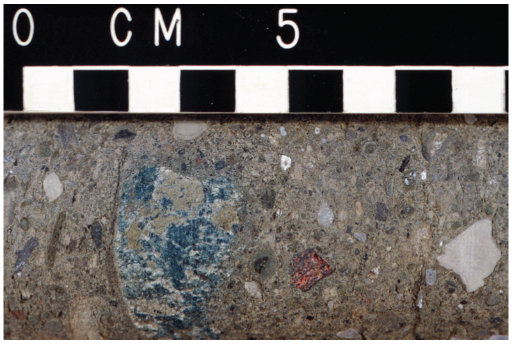

FIGURE 20—Baldwin Creek kimberlite at 230 ft. Many xenoliths, garnet, and chrome diopside.

Because of the fragile nature of the rock, only limited thin section examination has been conducted (Appendix D); however, initial analyses show the rock to be very similar to that of the Tuttle kimberlite.

Tuttle Kimberlite

The Tuttle kimberlite is very similar in appearance to the Baldwin Creek kimberlite. It is a micaceous kimberlite and tentatively classified as diatreme facies. The upper 154 ft (47 m) is a yellowish-gray-green, soft, weathered material containing abundant garnets and ilmenite. In the interval between 154–223 ft (47–68 m) the color changes to a medium gray. The interval contains several percent phlogopite (fig. 21), much of which has been altered to other forms of mica. Secondary sulfides (probably pyrite or marcasite) are also common (fig. 22) and are closely associated with mica (Appendix E). Below 223 ft (68 m) the rock becomes more competent and satin-spar-filled fractures up to 1.6 inches (4 cm) thick as well as rounded masses of gypsum up to 1.2 inches (3 cm) are abundant. Garnets (fig. 23) up to 0.8 inch (2 cm) and ilmenite up to 1.2 inches (3 cm) in size occur throughout most of the core.

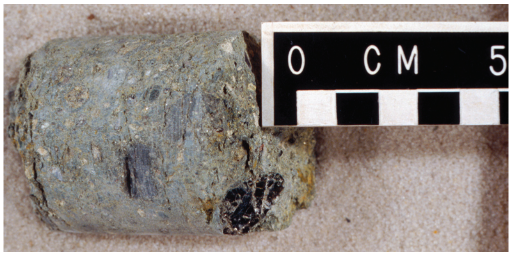

FIGURE 21—Tuttle kimberlite at 209 ft, showing phlogopite books.

FIGURE 22—Sulfides in the Tuttle kimberlite at 212 ft 6 inches.

FIGURE 23—Garnet in Tuttle kimberlite at 289 ft 3 inches.

Thin-section examination shows the Tuttle kimberlite to be tuffisitic (Appendix F). The texture of the rock is very similar throughout and can be described as inequigranular, pseudo-conglomeratic, massive, nondirectional, and locally slightly brecciated. Xenoliths up to 0.8 inch (2 cm) are common. The groundmass occupies about 20–30% of the rock volume. It consists predominantly of a mixture of very fine grained serpentine minerals, as well as opaque minerals, and locally, calcite crystals. The groundmass also contains abundant microcrysts, with some that can be recognized as consisting of serpentine, micas, chlorite, opaque minerals, and possibly phyllosilicates.

Phenocrysts can make up to 20% of the rock volume. They are usually rounded, ovoid, or discoidal in shape. They consist of phlogopite, and occasionally biotite and chlorite. Serpentine pseudomorphs after olivine are not very common. In a sample at 210 ft 9 inches (64 m) a few Cr-diopside phenocrysts are present. One large phenocryst of diopside is included into an ovoid kimberlite xenolith. It has a keliphitic rim around fresh diopside in the center.

Garnets are common. In a sample at 91 ft 7 inches (28 m), a 0.31-inch (0.8-cm) garnet occurs within a 0.59-inch (1.5-cm) xenolith of dark, micaceous kimberlite. Microprobe analyses show the garnet to be pyrope. The garnet has a narrow keliphitic rim consisting of aggregates of phyllosilicates and spinels. A few small sphene grains are also present. Opaque minerals consist of anatase altered to secondary ilmenite, chromite, magnetite, secondary hematite, and sometimes limonite. A thin layer of fine-grained serpentine with small admixtures of phyllosilicates rims the majority of phenocrysts.

Xenoliths can be divided into two types. The majority of them (up to 70%) are xenoliths of different kimberlites. They pose a problem, because they are difficult to distinguish from autoliths and pelletal lapilli. Common xenoliths are light-green fragments of kimberlite, which consist of fine-grained serpentine similar to that found in the matrix. Some of these are probably fragments of peridotite or dunite kimberlites. Others, characterized by a larger content of mica and chlorite microcrysts, are probably fragments of lamprophyre-type kimberlites. These types of xenoliths are primary phases crystallizing from the kimberlite magma. One large microdiorite xenolith occurs in the core at 264 ft (80.5 m).

The second type of xenolith is fragments of country rock. They are generally less common (up to 30%) and usually much larger in size. Various types of limestone and shale are the most common.

Methods

Electron microprobe analyses on polished rock samples were carried out on a “Camaca sx100” machine in the Inter-Institutional Laboratory of Microanalysis of Minerals and Synthetic substances at the Faculty of Geology at Warsaw University, Poland, under the direction of Dr. P. Dzierzanowski and analyst L. Jezak. Beam energy was 15 kV; beam current was 20 nA. Standards of natural and synthetic minerals were used.

The samples selected for analyses were those with the fewest xenoliths of those available. In addition, the small calcite veins were not included in the sampling.

Most of the major elements, Rb, and Sr were analyzed by atomic absorption using standard methods. All samples were analyzed for Fe, Na, K, La, Ce, Sm, Eu, Tb, Yb, Lu Ba, Th, Hf, Ta, Co, Sc, and Cr by neutron activation at Kansas State University. The samples of Antioch, Tuttle, and Baldwin Creek were also analyzed for the major elements Rb, Ba, Sr, Y, Zr, and Nb by XRF at the SRS company in Toronto, Ontario. Samples from the Randolph #1 and the Antioch cores were also analyzed by ICP-MS at the SRS company. The same elements analyzed by different methods agreed well and were averaged.

The samples analyzed by atomic absorption generally have a precision of better than 5 to 6%. Those analyzed by neutron activation have a precision of better than 5%. Those analyzed by atomic absorption have a precision better the 4%. Standard rocks continue to be analyzed at Kansas State, and they agree well with accepted values.

Also see the results of a standard basalt, BIR-1 analyzed by XRF and ICP-MS in our study on lamproites (Cullers et al., 1985).

Results and Discussion

Mica Compositions

The compositions of groundmass mica from the Antioch kimberlite are given in table 2 and fig. 24. The mica is notably high in Al_2O_3, BaO, and F and low in FeO_2 and TiO_2 compared to mica from most other kimberlites (Bardet, 1974; Beard et al., 2000; Dobbs et al., 1994; Egorov et al., 1991; McCallum et al., 1975; Mitchell, 1978; Tompkins et al., 1999). Some kimberlites, however, have mica compositions that are called kinoshitalite if enough Ba is present (Mitchell and Meyer, 1980; O’Brien and Tyni, 1999). Such Ba- and Al-rich and Ti- and Fe-poor micas are part of the main and characteristic evolutionary trend of kimberlites from phlogopite to the kinoshitalite end member (Mitchell, 1995). This evolutionary trend confirms that these rocks are kimberlite rather than orangeite.

TABLE 2—Mineralogic composition of Ba-rich groundmass mica from the Antioch kimberlite.

	Weight percent element oxides													
Date	20-Jul-01													
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14
SiO_2	28.789		29.744	33.905	32.393	31.375	30.746	28.387	26.986	33.292	32.66	32.346	33.833	31.697
TiO_2	0.255	0.37	0.701	0.362	0.351	0.435	0.46	0.314	0.272	0.333	0.278	0.528	0.345	0.462
Al_2O_3	18.276	17.847	15.06	14.894	15.551	16.586	16.523	16.779	17.12	15.558	15.22	16.016	14.582	14.565
MgO	25.041	23.138	24.441	24.504	24.018	23.912	23.134	22.421	21.986	24.666	24.272	24.104	24.629	23.091
MnO	0	0.081	0.111	0	0	0.062	0.148	0.074	0.093	0.059	0	0.02	0	0
FeO	1.086	1.323	9.086	1.38	1.307	1.038	1.454	1.261	1.291	1.384	1.183	1.321	1.362	1.178
BaO	20.82	18.715	13.42	12.962	13.898	16.007	16.025	19.072	21.484	14.034	13.486	14.674	13.02	13.083
K_2O	2.835	4.007	4.976	6.12	5.985	5.083	5.141	3.909	3.085	5.594	5.883	5.584	6.26	6.37
H_2O	2.315	2.532	2.709	2.477	2.304	2.601	2.557	1.982	2.101	2.402	2.364	2.658	2.497	2.087
F	3.078	2.488	2.319	2.902	3.13	2.494	2.471	3.374	2.983	3.077	2.996	2.452	2.834	3.328
Total	102.495	99.754	102.567	99.506	98.937	99.593	98.659	97.573	97.401	100.4	98.342	99.703	99.362	95.861
	Structural formula of mica based on 22 oxygens													
Si	4.574	4.726	4.683	5.277	5.128	4.973	4.945	4.752	4.604	5.171	5.175	5.077	5.282	5.187
Ti	0.031	0.045	0.083	0.042	0.042	0.052	0.056	0.040	0.035	0.039	0.033	0.062	0.040	0.057
Al	3.422	3.398	2.795	2.732	2.901	3.098	3.132	3.311	3.442	2.848	2.842	2.963	2.683	2.809
Mg	5.931	5.573	5.737	5.685	5.668	5.65	5.547	5.596	5.591	5.712	5.733	5.64	5.732	5.633
Mn	0	0.011	0.015	0	0	0.008	0.021	0.010	0.013	0.008	0	0.003	0	0
Fe	0.144	0.179	1.196	0.18	0.173	0.138	0.196	0.176	0.184	0.180	0.157	0.173	0.178	0.161
Ba	1.296	1.185	0.828	0.791	0.862	0.994	1.01	1.251	1.436	0.854	0.837	0.903	0.797	0.839
K	0.575	0.826	1.000	1.215	1.209	1.028	1.055	0.835	0.671	1.108	1.189	1.118	1.247	1.330
H_2O	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	-1.296	-1.048	0.976	-1.222	-1.318	-1.05	-1.04	-1.421	-1.256	-1.296	-1.262	-1.033	-1.193	-1.401
Total	14.677	14.895	17.313	14.7	14.665	14.891	14.922	14.55	14.72	14.624	14.704	14.906	14.766	14.615

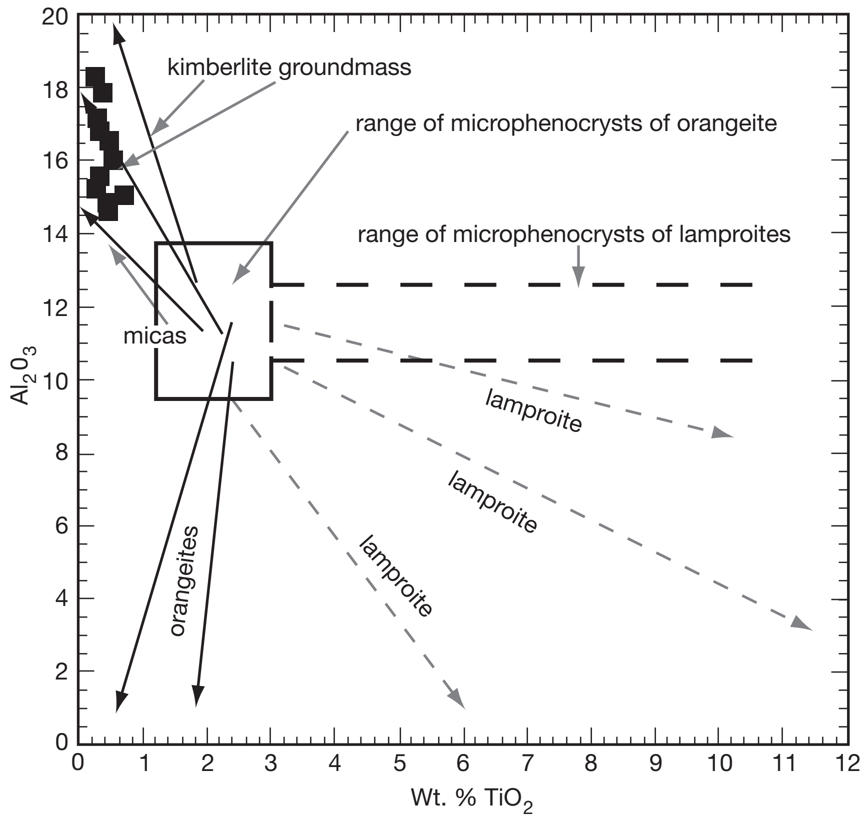

FIGURE 24—Composition of groundmass mica from the Antioch kimberlite.

Major Elements

Introduction

The major element compositions of the kimberlites in this study are given in table 3. Samples from previous studies of the Randolph #2, Leonardville, Bala, Randolph #1, and Stockdale kimberlites are summarized along with samples analyzed in this study (Brookins, 1970; Cullers et al., 1982).

Contamination

The Stockdale, Winkler, Lone Bush, Lone Tree, Baldwin Creek, Tuttle, and parts of the Antioch kimberlites are composed of moderate to abundant crustal xenoliths so that they are likely contaminated with varied amounts of mudrocks and lesser limestones. Some kimberlites like Tuttle and Antioch also contain abundant fragments of other kimberlite and serpentinized peridotite or dunite. The Randolph #1 and parts of the Antioch kimberlites have the fewest crustal xenoliths. The Swede Creek, Randolph #2, Leonardville, and Bala kimberlites have intermediate amounts of crustal xenoliths between these two extremes.

The amount of crustal contamination is believed to be reflected in the contamination index (CI = (SiO_2+Al_2O_3+Na_2O)/(MgO+K_2O) as weight percent) (Clement, 1982). A CI of about 1 for kimberlites is considered to be uncontaminated and greater values represent greater degrees of contamination (Clement, 1982). The CI's are the highest (i.e., greater than 1.5) for the Winkler, Lone Bush, Lone Tree, Tuttle, Baldwin Creek, and the middle portion of the Antioch kimberlites (table 3, fig. 1) and consistent with their moderate to abundant xenoliths. Curiously the Stockdale kimberlite has a CI of about 1 even though it contains about 20% xenoliths. Evidently the high MgO in the Stockdale must have lowered the CI compared to the other xenolith-rich samples. As expected, the Swede Creek, Randolph No. 2, Leonardville, Bala, Randolph No. 1, and parts of the Antioch kimberlites contain lower CI's (1.0 to 1.37; table 3, fig. 25). Note the increasing CI with Al_2O_3 of the kimberlites falls in line with an average of midcontinent platform shales (Cullers, 2002) consistent with the abundant shale xenoliths with much higher SiO_2 and Al_2O_3 and lower MgO than the kimberlites.

Classification

Kimberlites (or Type I kimberlites) are undersaturated rocks (wgt% SiO_2 = 25-35) with low Na_2O/K_2O ratios (<0.5), low Al_2O_3 (wgt.% Al_2O_3<5) and high LOI (wgt% LOI> 10) (Mitchell, 1986; Mitchell, 1995). The least contaminated Riley County samples certainly have these characteristics (tables 3 and 4). These major element characteristics distinguish these samples from evolved orangites (Type II kimberlites), but are not distinctive of unevolved orangites (Mitchell, 1995).

A distinguishing difference between kimberlites and unevolved orangites is the higher TiO_2 and lower K_2O in kimberlites than in unevolved orangites (Smith et al., 1985). The Riley County kimberlites plot in the high TiO_2 and low K_2O field of kimberlites rather than unevolved orangites, thus confirming that they are kimberlites (fig. 26). The high TiO_2 is likely due to titanium-rich magnetite and ilmenite, and the low K_2O is due to the minimal amount of K-rich phlogopite or other K-rich minerals. Finally, unevolved orangites should have molar

TABLE 3—Elemental concentrations of Riley County kimberlites.

	Lone Bush surface	Lone Tree surface	Swede Creek surface	Winkler surface	Randolph #2 surface	Leonard-ville[2] surface	Bala[2] surface	Randolph #1[2] surface	Stock-dale[2] surface		Antioch 76'6" depth	Antioch 152'5" depth	Antioch 282'2" depth	Tuttle 89'8" depth	Tuttle 270'2" depth	Baldwin Ck. 114'7" depth	Baldwin Ck. Baldwin Ck. 291'6"
Number of Samples[1]	‘(3)	‘(3)	‘(3)	‘(3)	‘(3)	‘(5)	‘(7)	‘(2)	‘(3)	Number of Samples	1	1	1	1	1	1	
	37.2	30.6	28.0	29.5	23.3	24.2	22.2	22.9	31.8	SiO_2	29.1	34.03	27.3	36.4	31.4	43.3	40.9
TiO_2	3.85	3.3	4.4	2.10	2.57	1.50	2.20	1.72	1.98	TiO_2	2.51	1.19	2.35	2.04	2.12	1.99	1.88
Al_2O_3	5.91	4.24	3.05	3.32	3.52	2.03	3.59	4.63	2.18	Al_2O_3	3.11	6.34	2.43	5.55	4.68	5.31	5.05
Fe_2O_3 (total)	11.90	11.90	9.74	6.63	11.43	8.55	10.4	10.0	8.54	Fe_2O_3 (total)	11.60	5.92	11.6	7.47	6.63	6.90	7.38
CaO	2.95	9.26	10.8	17.5	13.60	15.9	13.07	16.68	5.69	CaO	6.79	14.35	9.39	6.04	14.23	6.89	7.57
MgO	15.4	23.3	25.8	18.5	24.3	24.45	25.5	20.36	33.52	MgO	29.19	19.67	28.4	27.3	21.17	22.36	21.99
K_2O	0.45	0.14	0.03	0.24	0.05	0.30	0.02	0.15	0.04	K_2O	0.04	0.58	0.04	1.2	1.84	0.37	0.87
Na_2O	0.06	0.06	0.12	0.04	0.04	0.30	0.04	0.51	0.01	Na_2O	0.15	1.03	0.14	0.12	0.72	0.94	1.86
MnO	0.25	0.27	0.23	0.08	0.24	0.08	0.21	0.14	0.14	MnO	0.21	0.06	0.23	0.15	0.15	0.08	0.12
P_2O_5								1.37		P_2O_5	0.91	0.53	1.25	0.38	0.32	0.3	0.29
LOI	21.4	17.0	17.6	21.9	20.2	21.4	20.9	21.24	16.7	LOI	15.4	15.05	16.2	12.9	14.1	10.07	9.30
Total	99.37	100.07	99.77	99.81	99.25	98.71	98.13	99.70	100.60	Total	99.01	98.75	99.33	99.55	97.36	98.51	97.21
$(K_2O + Na_2O)/Al_2O_3$-1	0.099	0.059	0.075	0.098	0.034	0.403	0.024	0.216	0.027	$(K_2O + Na_2O)/Al_2O_3$	0.093	0.366	0.113	0.270	0.679	0.367	0.792
K_2O/Na_2O-1	4.94	1.54	0.16	3.95	0.82	0.66	0.33	0.19	2.63	K_2O/Na_2O	0.18	0.37	0.19	6.58	1.68	0.26	0.31
	2.72	1.49	1.21	1.75	1.10	1.07	1.01	1.37	1.01	contam. index[3]	1.11	2.04	1.05	1.48	1.60	2.18	2.09
K_2O/Al_2O_3-1	0.08	0.04	0.01	0.08	0.02	0.16	0.01	0.04	0.02	K_2O/Al_2O_3	0.01	0.10	0.02	0.23	0.43	0.08	0.19
La	94.7	99.0	184	42.6	228	152	302	233	89	La	261	106	255	51.8	56.4	72	49.4
Ce	151	160	268	65.0	451	243	516	395	142	Ce	444	195	415	89.5	95.4	113	86.8
Pr								37.2		Pr	40.3	17.8	38.1				
Nd								122		Nd	130	59.3	121				
Sm	9.74	8.05	11.2	5.2	21.4	10.9	18.3	15.4	6.7	Sm	15.1	8.0	14.3	5.34	5.08	6.23	5.47
Eu	2.20	1.88	2.85	0.92	4.81	2.9	4.56	3.7	1.75	Eu	3.48	1.9	3.33	1.18	1.16	1.26	1.25
Gd								9.1		Gd	8.7	5.11	8.7				
Tb	0.62	0.41	0.34	0.19	0.81	0.78	1.07	0.90	0.50	Tb	0.91	0.7	0.91	0.46	0.39	0.48	0.45
Dy								4.63		Dy	3.87	3.53	3.65				
Ho								0.74		Ho	0.63	0.64	0.59				
Er								1.88		Er	1.67	2.06	1.55				
Yb	1.66	0.55	0.31	0.55	1.1	0.85	1.24	1.49	0.82	Yb	1.3	1.66	1.31	1.30	1.06	1.65	1.77
Lu	0.21	0.14	0.034	0.13	0.15	0.16	0.26	0.21	0.12	Lu	0.17	0.25	0.18	0.20	0.16	0.26	0.25
$(La/Lu)_{cn}$	46	69	540	34	197	97	133	106	76	$(La/Lu)_{cn}$	153.5	42.4	141.7	25.9	35.3	27.7	19.8

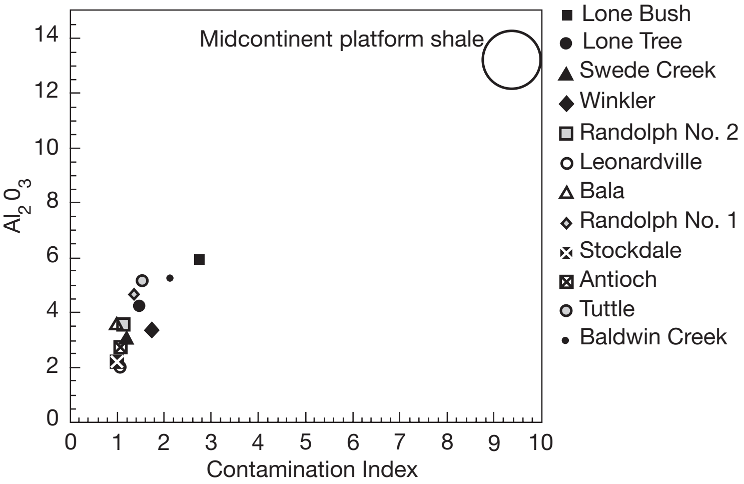

FIGURE 25—Contamination index (CI) of Swede Creek, Randolph #2, Leonardville, Bala, Randolph #1, and parts of the Antioch kimberlites.

$(K_2O + Na_2O)/ Al_2O_3 > 1$, molar $K_2O/Na_2O > 3$, and $K_2O/Al_2O_3 > 1$ (Mitchell, 1995). None of the uncontaminated samples in this study has these characteristics (tables 3 and 4). Some of the contaminated samples have $K_2O/Na_2O > 3$, but this may be due to contamination with illite-rich shales with high K_2O/Na_2O ratios. Thus, these characteristics are also consistent with these samples being kimberlites rather than unevolved orangites.

Trace Elements

The Riley-Marshall County kimberlites, like other kimberlites and orangites (Mitchell, 1986; Mitchell, 1995), contain relatively high Cr, Ba, Sr, La, Ce, and $(La/Lu)_{cn}$ ratios compared to many other mantle-derived rocks like basalts (table 4). Other trace element contents are more similar to mantle-derived rocks. Orangites and kimberlites do not differ significantly in most trace element contents except for Rb (Mitchell, 1995). The Rb in orangites is generally greater than 110, and it is less than 110 in kimberlites (Mitchell, 1995). The very low Rb of the Riley–Marshall county kimberlites (table 4) is again consistent with them being kimberlites rather than orangites.

Samples of relatively uncontaminated Antioch and Randolph #1 kimberlites are plotted relative to primitive mantle (Sun and McDonough, 1989) in fig. 27. These were used because they have the most data. Most elemental concentrations, like most kimberlites (Clement, 1982; Mitchell, 1995; Price et al., 2000; Spriggs, 1988), are greatly enriched relative to the primitive mantle. The Ba, Th, Nb, La, and Ce concentrations are the most enriched. The K and Rb concentration ratios are anonymously low, and the Sr, P, and Zr ratios are slightly low compared to adjacent elements. These trends are similar to those in other kimberlites and orangites (Mitchell, 1995; Price et al., 2000; Seggie et al., 1999). Standard interpretation for the enriched Ba, Th, Nb, La, and Ce is that the source is enriched in these elements with no residual mineral that retains these elements during the small degrees of melting (Mitchell, 1995). The negative K and Rb anomalies have been explained by assuming that a phase like phlogopite or K-richterite remains in the source during melting (Mitchell, 1995). The negative Sr anomaly could also be due to a residual phosphate mineral like apatite left in the residual solid, or to depletion of clinopyroxene due to a previous melting episode to form basalt (Mitchell, 1995). Low Yb and Lu relative to the high light REE have been interpreted to be due to garnet being in the residuum during small degrees of melting (fig. 28) (Cullers et al., 1982). The lack of an Eu anomaly has been interpreted to mean that no feldspar-melt fractionation occurred during melting or crystallization (Cullers et al., 1982).

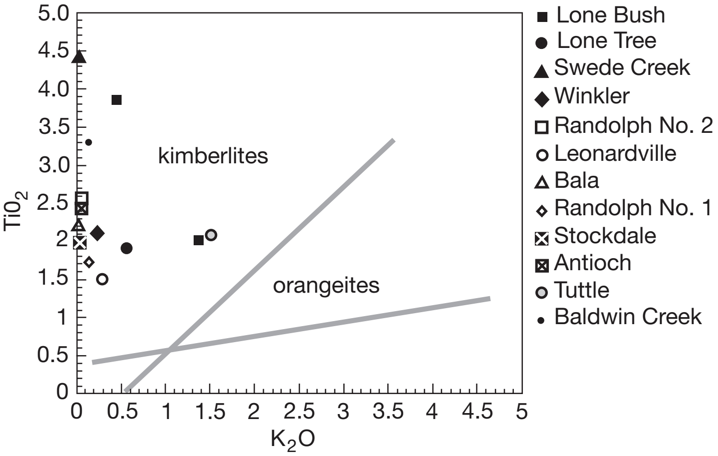

FIGURE 26—Plot of TiO_2 and K_2O in Riley County kimberlites.

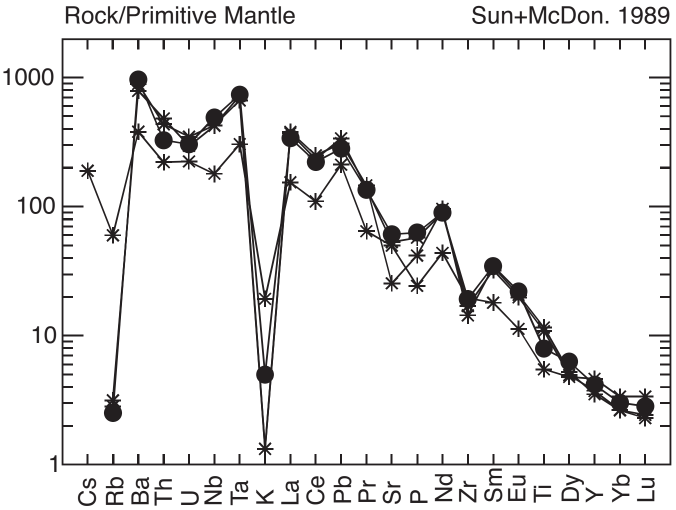

FIGURE 27—Plot of relatively uncontaminated Antioch and Randolph #1 kimberlites relative to primitive mantle.

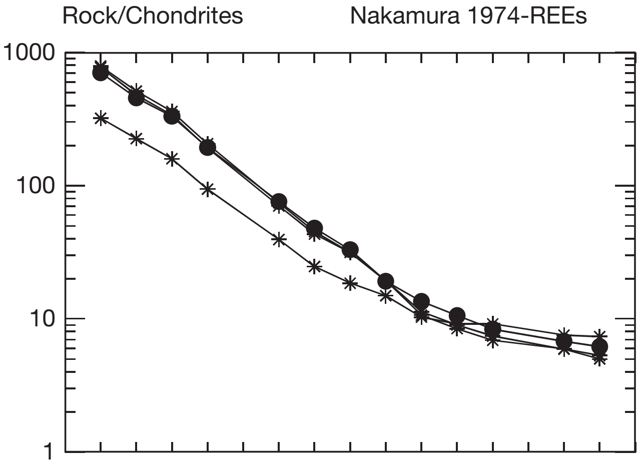

FIGURE 28—Plot of Yb and Lu relative to the high light REE.

TABLE 4—Range of the compositions of samples in this study with kimberlites, unevolved orangites, and evolved orangites.

	Least contaminated kimberlites this study	**Type I kimberlites** [1]	**Unevolved Type II kimberlites or orangites** [1]
SiO_2	22.2-31.8	16.4-37.5	27.6-40.4
TiO_2	1.5-4.4	0.38-4.7	0.43-2.52
Al_2O_3	2.0-4.6	0.61-4.38	0.91-6.0
Fe_2O_3(total)	8.5-11.6	7.3-13.7	5.1-10.3
CaO	5.69-16.7	2.1-24.8	2.9-24.5
MgO	20.4-33.5	21.9-38.6	10.4-39.5
K_2O	0.02-0.3	0.02-2.9	0.52-6.7
Na_2O	0.01-0.51	0.01-1.0	0.01-0.74
MnO	0.08-0.24	0.11-0.85	0.09-0.46
P_2O_5	0.91-1.37	0.21-2.2	0.1-3.31
LOI	15.4-21.4	3.1-16.3	5.3-21.5
$(K_2O + Na_2O)/Al_2O_3$	0.024-0.40	not given	not given
K_2O/Na_2O	0.16-2.6	not given	not given
contam. index [2]	1.01-1.37	not given	not given
K_2O/Al_2O_3	0.01-0.16	not given	not given
La	89-302	21-301	41-504
Ce	142-516	43-529	82-871
Sm	6.7-18.3	2.2-28.5	4.8-32.3
Eu	1.75-4.81	0.4-11.2	1.14-10.5
Tb	0.34-1.07	0.61-2.6	0.06-3.31
Yb	0.31-1.61	0.49-1.38	0.25-5.77
Lu	0.034-0.26	0.03-0.30	0.02-0.36
$(La/Lu)_{cn}$	76-540	not given	not given
Rb	<3-10	26-111	43-305
Ba	2650-8450	164-2292	290-16300
Sr	514-2010	186-2428	416-6591
Th	11.9-55	5.3-27	5.2-74
Hf	2.6-6.6	2.5-15	3.1-15
Zr	289-344	73-717	53-1060
Ta	18-33	2.2-23	2.2-26
Co	58-84	9-125	54-1121
Sc	10.5-27.8	6.1-38	2.1-39
Ni	315-881	not given	not given
Cr	1020-1571	430-2554	315-2865
Cs	not given	not given	not given
Y	32-48	not given	not given
U	6.2-7.3	not given	not given
Pb	20-24	not given	not given
Nb	302-350	37-346	2-289

1—from Mitchell, 1986, 1995

2—contamination index defined in the text

Review of Petrogenesis

A major problem in interpreting the origin of kimberlites from the chemical composition is their hybrid nature. Kimberlite magmas contain not only primary phases such as phenocrysts and groundmass, but also xenoliths and xenocrysts (Mitchell, 1995). For example, kimberlites often contain high Ni concentrations (> 1,000 ppm) due to the incorporation of olivine xenocrysts likely derived from the peridotite source rocks (Mitchell, 1995). Also, the contamination of the Riley–Marshall County kimberlites by mudrocks and limestones previously has been discussed.

Earlier hypotheses for the formation of kimberlites in Riley–Marshall counties or kimberlites similar to them have centered around very small degrees of melting of phosphate-titanite-phlogopite-garnet lherzolite (Cullers et al., 1982; Mitchell and Brunfelt, 1975; Paul et al., 1975). Such small amounts of partial melting (less than 1%) could produce the high concentrations of incompatible elements and $(La/Lu)_{cn}$ ratios and low K_2O ratios in the kimberlites. Later melting models used metasomatized apatite-K-Ti richterite-garnet residues that allowed greater degrees of partial melting (Dawson, 1984; Mitchell, 1986).

Another model involves a three-stage process of depletion, enrichment, and melting to explain the trace element contents (Tainton and McKenzie, 1994). The depletion event involves a small percent partial melting of a garnet lherzolite that reduced the incompatible elements in the residue, but retains the HREE. The depleted incompatible element residue was then metasomatized with an incompatible element-enriched fluid. Melting of this solid then produced kimberlites and orangites. Phlogopite is again used to reduce the K content of the kimberlites. Because the D.C.'s of mineral-kimberlite melts are only poorly known, detailed calculations using trace element modeling are only crudely approximate.

Aphanitic or glassy samples of kimberlites without many phenocrysts, xenocrysts, or xenoliths would be most appropriate to approximate the melt phase of kimberlites (Price et al., 2000). None of the Riley–Marshall County kimberlites contain minimal combinations of phenocrysts, xenocrysts, and xenoliths. The Randolph #2 and Swede Creek kimberlites contain the fewest phenocrysts, xenocrysts, and xenoliths, so these kimberlites may be the best to approximate the original melt composition. The xenoliths in much of the Antioch kimberlites are mostly kimberlite, peridotite, dunite, or lamprophyre with few phenocrysts. These three kimberlites have moderately high Mg #'s (100(Mg/(Mg + Fe) = 65 to 70)), MgO concentrations (24.3 to 29.2 wgt%), and Cr concentrations (1,170–1,571 ppm) and low SiO_2 (23.3 to 29.2 wgt%). Unfractionated kimberlites have been suggested to contain Mg#'s of 83 to 84, MgO = 27 wgt%, Cr = 2,400 ppm, and SiO_2 =23.6 wgt% (Arima and Inoue, 1995; Arima et al., 1993; Mitchell, 1995). The lower Mg #'s and Cr concentrations of the Riley–Marshall County kimberlites suggests that some fractionation or contamination has occurred from the primary melt compositions. Thus, it is not practical except in the most general terms to comment on the origin of these kimberlites.

Experimental studies suggest that a low-percent partial melting of carbonate-bearing lherzolite may produce kimberlite magma at depths of 200 km (Canil and Scarfe, 1990; Dalton and Presnall, 1998; Edgar and Charbonneau, 1993; Eggler, 1978; Wyllie, 1977; Wyllie, 1980; Wyllie and Lee, 1999). Average kimberlites are in the higher-temperature part of the harzburgite field, however, at 100-km depth (Wyllie and Lee, 1999). Such models are consistent with the low Al_2O_3 and SiO_2 contents and the high CO_2, incompatible elements, and LREE/HREE ratios of the kimberlites.

A small percent melting (up to 1%) at 6 Gpa of a composition similar to a carbonate-bearing peridotite in the system $CaO-MgO-Al_2O_3-SiO_2-CO_2$ produced carbonatite-like melts at the solidus but kimberlite melts at 70 to 100° C above the solidus (Dalton and Presnall, 1998). The compositions of the experimental melts and the kimberlite compositions were plotted in the $CaO-MgO-SiO_2$ projections, and the presumed primary kimberlites were found to coincide with experimental compositions at 0.7 to 0.9% melting (Price et al., 2000). Of course, the experimental system is not as complex as the natural system due to the lack of Fe and H_2O in the experimental system. The relatively uncontaminated Riley–Marshall County kimberlites are plotted in the $CaO-MgO-SiO_2$ system in fig. 29 along with the more contaminated kimberlites. The least-contaminated kimberlites appear to plot close to the experimental data at higher MgO and CaO contents than the more contaminated kimberlites so at least the results are consistent with the possibility that melting of a carbonate-bearing garnet lherzolite formed them. The more contaminated Riley County kimberlites tend to plot at higher SiO_2 and lower CaO and MgO concentrations consistent with their contamination with sedimentary rocks.

More recent experimental studies of the crystallization of an aphanite kimberlite suggests that kimberlites may not form by such small degrees of melting of a carbonated garnet lherzolite as

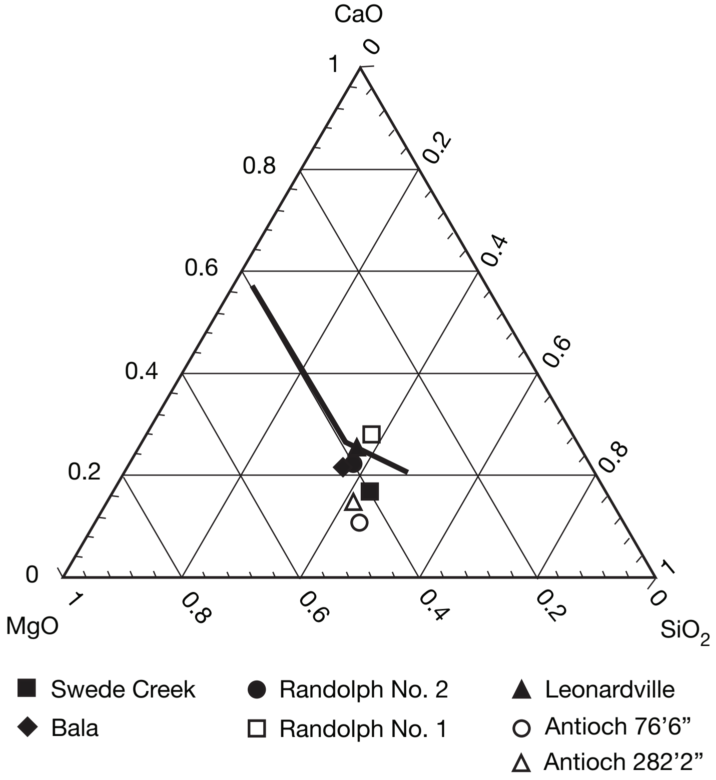

FIGURE 29—Plot of relatively uncontaminated Riley–Marshall County kimberlites in the $CaO-MgO-SiO_2$ system along with more contaminated kimberlites.

suggested by other studies (Mitchell, 2004). Instead, kimberlites may possibly form by 10 to 50% melting of a varied mix of complex, carbonate-bearing veins and lherzolite-harzburgite (Mitchell, 2004). This hypothesis helps to eliminate the need to separate the melt from residue during with less than 1% melting. Also complex arguments to explain the high LREE/HREE ratios and high incompatible element contents in kimberlites, such as having garnet in the residue and no minerals that concentrate the incompatible elements, are not needed. Instead, the incompatible elements are present in apatite and/or perovskite of the source so that trace element and LREE/HREE ratios of the kimberlite melt are more of a reflection of the content of the source as the accessory minerals completely melt (Mitchell, 2004).

Thus, a small percent partial melting of a garnet-carbonate-peridotite or a larger percent melting of a complex mix of carbonate-bearing veins and lherzolite-harzburgite for the Riley–Marshall County kimberlites are consistent with hypotheses suggested by the experimental data. In addition, phlogopite or K-richterite was likely in the residuum to explain the low K_2O contents. These kimberlites were, however, moderately to extensively contaminated with various amounts of crustal shales, carbonates, and igneous rocks-minerals so that the fractionation trends are difficult to decipher.

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Appendix A—Antioch kimberlite

6’6”-21’2”	Set 6 ft of 6-inch casing. Drilled to 21 ft 2 inches, then hit hard kimberlite. Set 3 inches casing and cement it in.
21’2”-24’9”	Recovered about 3 ft of kimberlite down to 24 ft 9 inches. Rock is dark-gray-green, hard. Rock contains small clasts that have the same color as the matrix. Vertical and horizontal thin carbonate stringers are present. Also some dark-red patches that appear to be oxidation of iron.
24’9”-28’9”	Drilled and recovered 4 ft down to 28 ft 9 inches. Good recovery. Vertical carbonate stringers are prominent. Red oxidation related to fractures or micro-fractures. The fresher rock appears to be more blue-gray-colored while the altered rock is more green-gray. Alteration is also related to fractures. Rock contains many small altered inclusions.
28’9”-36’9”	Drilled 8 ft down to 36 ft 9 inches, but may not have recovered all the core. Lost circulation. In the core are two subhorizontal calcite-lined fractures that are probably open. The kimberlite looks the same as above.
36’9”-38’9”	Drilled 2 ft recovered 2 ft 11 inches down to 38 ft 9 inches. Kimberlite as above. No fractures in this interval that seem to be open.
38’9”-48’9”	Drilled and recovered 10 ft down to 48 ft 9 inches. Kimberlite as above. Lots of open fractures.
48’9”-55’8”	Drilled 7 ft 4 inches and recovered 6 ft 11 inches down to 55 ft 8 inches. Kimberlite as above. One large vertical open fracture. No garnet or ilmenite visible in the core.
55’8”-58’11”	Drilled and recovered 3 ft 3 inches down to 55 ft 11 inches. Kimberlite as above. No major fractures.
58’11”-68’11”	Drilled and recovered 10 ft down to 68 ft 11 inches. Kimberlite as above. Several large open fractures that are near vertical.
68’11”-78’9”	Drilled 10 ft recovered 9 ft 10 inches down to 78 ft 9 inches. Kimberlite as above. Still open fractures. Rock does not change character.
78’9”-88’7”	Drilled 10 ft, recovered 9 ft 10 inches down to 88 ft 7 inches. Still the same rock with open fractures.
88’7”-98’7”	Drilled and recovered 10 ft down to 98 ft 7 inches. Rock same as above. Still some rusty spots.
98’7”-102’1”	Drilled and recovered 3 ft 6 inches down to 102 ft 1 inches. Rock as above.
102’1”-108’8”	Drilled 6 ft 6 inches recovered 6 ft 7 inches down to 108 ft 8 inches. Same as above.
108’8”-117’9”	Drilled and recovered 9 ft 1 inch down to 117 ft 9 inches. Rock same as above. At about 115 ft a fairly rapid change to lighter-gray-green, softer kimberlite, having larger and more numerous clasts.
117’9”-122’5”	Drilled 5 ft recovered 4 ft 8 inches. There may be gypsum-filled fractures that are washed out and the driller might have left some in the hole. Driller’s depth 123 ft 2 inches. My depth 122 ft 5 inches.
122’5”-128’4”	Drilled 5 ft 10 inches recovered 5 ft 11 inches. My depth 128 ft 4 inches. The driller drilled to 129 ft, but drill stem is down to 130 ft 4 inches. May have a void up to 1 ft wide. It appears that there are softer intervals, especially towards the bottom.
128’4”-131’	Recovered ~1 ft of relatively solid rock. Rock appears to have more and larger inclusions.
131’-135’2”	Drilled 4 ft 2 inches recovered ~3 ft. Still incompetent core that falls apart easily.
135’2”-138’9”	Should be down at 138 ft 9 inches. The driller measured 138 ft 10 inches. Rock still broken up into pieces no longer than 2–3 inches. Recovered ~3 ft.
138’9”-142”	Drilled 3 ft 2 inches down to 142 ft. Probably recovered most of it in small broken-up pieces, except for one piece about 9 ft long. Rock still much the same. Don’t see any obvious calcite-filled fractures, but gypsum is apparent.
142”-148’10”	Drilled 10 ft recovered ~6 ft 6 inches. Top 3 ft 2 inches undisturbed. Had to blow part of the core out of the barrel. Lower ~2 ft also undisturbed. Core maybe a bit harder.
148’10”-158’10”	Drilled and recovered kimberlite down to 158 ft 10 inches. Rock is more competent, but still has cavities—some of which are filled with pink carbonate?
158’10”-168’10”	Drilled 10 ft and recovered 9 ft 2 inches. Depth 168 ft 10 inches. Big vug at the bottom of the hole (~10 inches). Rock the same as above.

168’10”-178’6”	Drilled 10 ft recovered 9 ft 8 inches. Depth probably 178 ft 6 inches. Some material lost or not present due to vugs. Rock a little more competent. Some carbonate, secondary infilling and a few large carbonate, unaltered clasts.
178’6”-188’4”	Drilled 9 ft 4 inches recovered close to 10 ft. Depth 188 ft 4 inches. Table collapsed, core fell on the ground and is out of order.
188’4”-194’6”	Drilled 6 ft 6 inches recovered 6 ft 2 inches down to 194 ft 6 inches. Had to use pressure to get it out of the barrel.
194’6”-197’8”	Drilled 4 ft 2 inches recovered 3 ft 10 inches. Bottom of core 197 ft 8 inches. Several large clasts that look like shale, one is about 5 inches long along the length of the core.
197’8”-207’8”	Drilled and recovered 10 ft. Several clasts up to 1 ft long. Depth 207 ft 8 inches. The middle part (3 ft 6 inches) is disturbed, because it fell out of the core barrel.
207’8”-208’10”	Drilled 1 ft 3 inches recovered 1 ft 2 inches. Depth 208 ft 10 inches. The whole interval is one large carbonate clast.
208’10”-217’8”	Drilled 8 ft 9 inches recovered 8 ft 10 inches. Depth 217 ft 8 inches. Rock is mostly altered limestone and shale clasts. Change to hard, dark-gray kimberlite.
217’8”-227’4”	Drilled 10 ft recovered 9 ft 8 inches. Depth 227 ft 4 inches. Mostly hard kimberlite like we found higher up in the hole. Dense and hard. No obvious fresh sedimentary clasts. Small, thin, calcite-filled fractures at angles up to 45°.
227’4”-232’	Drilled 5 ft recovered 5 ft 6 inches. Depth 232 ft. Hard kimberlite.
232’-237’10”	Drilled 5 ft recovered 5 ft. Depth 237 ft 10 inches. Hard kimberlite. Rapid change to green-gray kimberlite at 233 ft 6 inches.
233’6”-247’8”	Drilled 10 ft recovered 9 ft 10 inches. Down to 247 ft 8 inches. Rock has many clasts, mostly sedimentary. Clasts are up to 1 ft long in the core.
247’8”-257’10”	Drilled 10 ft, recovered 10 ft 2 inches. Down to 257 ft 10 inches. Rock the same as above, but there are some isolated calcite-filled vugs up to 1 inch in diameter. Large clasts common.
257’10”-267’6”	Drilled 10 ft recovered 9 ft 8 inches down to 267 ft 6 inches. Rock as above. At 264 ft 7 inches the rock changes to the dark-gray kimberlite having only tiny, mm-size inclusions.
267’6”-268’	Went back in and recovered 6 inches left in the hole
268’-276’9”	Drilled 10 ft recovered 8 ft 9 inches to 276 ft 9 inches. Dark hard kimberlite.
276’9”-277’11”	Retrieved another 1 ft 2 inches of same kimberlite
277’11”-287’11”	Cored and retrieved 10 ft down to 287 ft 11 inches. Kimberlite as above.
287’11”-298’1”	Cored 10 ft recovered 10 ft 2 inches down to 298 ft 1 inch. Same kimberlite as above.
298’1”-307’11”	Drilled 10 ft recovered 9 ft 10 inches down to 307 ft 11 inches. Same kimberlite as above.

End of hole.

Appendix B—Petrology and mineralogy of the Antioch kimberlite based on thin section examination

A-6 sample: TUFFISITIC KIMBERLITE with large xenolith (megaxenolith) of micritic carbonate (limestone) (195 ft 2 inches)

Texture: similar to texture of the samples described above (excluding T-6 and T-8) (inequigranular, pseudo-conglomeratic, massive, and nondirectional). Xenoliths are up to 30 mm in diameter.

Groundmass occupies about 20–30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, micas, opaque minerals and abundant of secondary calcite crystals and/or nests. Due to relatively large contents of dark mica microcrysts, the whole kimberlite is also much darker than kimberlites described above (samples T-l–T-10, excluding T-8).

Phenocrysts are extremely rare (about 1% of the rock volume). Only few micas and serpentine pseudomorphs were observed.

Xenoliths are the main component of the sample A-6, exceeding about 70–80 volume % of the sample. Xenoliths of different kimberlites are very rare. They are peridotite–dunite (olivine rich) kimberlite xenoliths as well as less common dark-green, lamprophyre (micaceous) xenoliths. They are spheroidal and oval in shape and usually very small (average size is about 1.0 mm). Xenoliths exhibit various effects of calcitization.

Xenoliths of country rocks are the main constituent of the rock. One megacryst of micritic limestone occupies about 70 % of volume of the whole sample. Micritic groundmass contains many small nests and ovoid lenses filled up with fine- and/or medium-grained calcite. Along slightly curved border with kimberlite a distinct zone about 15 mm wide is visible. It consists of calcite crystals, which are slightly coarser than the rest of limestone.

The difference in calcite crystallinity probably resulted from thermal and/or kinetic effect of kimberlite emplacement.

Other xenoliths of country rocks are small (about 2 mm in average) and are represented by similar amount of clayey shales and fine-grained and/or micritic limestones.

Kimberlitic part of the rock contains relatively larges amount of secondary calcite, which forms isolated grains and/or small nests. Such a strong calcitization resulted probably from close vicinity of large xenolith of limestone.

A-7 sample: Transition between TUFFISITIC KIMBERLITE and HYPABYSSAL KIMBERLITE (?) (200 ft 2 inches)

Texture: quite homogenous (different than texture of samples T-l to T-10; however, still inequigranular), pseudo-conglomeratic up to pseudo-sandy, massive, and unoriented (nondirectional). Xenoliths are up to 10 mm in diameter.

Groundmass occupies about 20–30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, micas, opaque minerals and abundance of secondary calcite crystals and/or nests. Due to relatively large contents of dark mica microcrysts, the whole kimberlite is also much darker than kimberlites described above (samples T-l–T-10, excluding T-8).

Phenocrysts are very rare (about 1% of the rock volume). Only few micas and serpentine pseudomorphs were observed. Some of micas are highly altered into hydro-micas.

Xenoliths are the main component of the sample A-6, exceeding about 70–80 volume % of the sample. Xenoliths of different kimberlites are very common. They are peridotite–dunite (olivine-rich) kimberlite xenoliths as well as similar amount of dark-green, lamprophyre (micaceous) xenoliths. They are spheroidal and oval in shape and differentiated in size—usually small (average size is about 1.0 mm) but a little bit larger, up to 10 mm in diameter, also occur. Xenoliths exhibit various effects of calcitization.

Xenoliths of country rocks are common constituent of the rock. They are represented by similar amount of clayey shales and fine-grained and/or micritic limestones. Besides, very few organogenic, highly recrystallized limestones were found.

Almost all limestone xenoliths are rimmed by thin rims of fine-grained calcite, mixed with serpentine and/or phyllosilicates (?).

A-10 sample: HYPABYSSAL KIMBERLITE (?) (230 ft 11 inches)

Texture: quite homogenous, fine to medium grained, porphyritic (not pseudo-conglomeratic anymore!), massive, unoriented (nondirectional). The sample under polarizing microscope looks like typical, highly altered volcanic or subvolcanic rock. Rare xenoliths are up to 5 mm in diameter. (Sample A-10 is very similar to samples A-13 and A-15.)

Groundmass is the main constituent of the rock. It occupies about 50–60% of the sample volume. It consists of very fine grained mixture of serpentine minerals, micas, opaque minerals, and secondary calcite crystals and/or nests. Opaque minerals are usually much smaller than serpentine pseudomorphs. However, in many cases serpentine nuclei is rimmed by opaque minerals. Due to relatively large contents of opaque minerals and dark mica microcrysts within groundmass, the whole kimberlite is also dark green.

Micro-phenocrysts are common but due to small size they occupy about 20% of the rock volume. They are represented mainly by colorless, fine-grained serpentine pseudomorphs after olivine, often showing idiomorphic contours. Majority of pseudomorphs is small (about 0.1 mm in size) and only few are larger, up to 1 mm in diameter. Many serpentine pseudomorphs are rimmed by opaque minerals and sometimes by very fine grained serpentine. Some of them contain various amount of secondary calcite, which sometimes forms medium- or even coarse-grained crystals.

Xenoliths are not very common component of sample A-10 and occupy not more than 20% of its volume. Only few small, rounded xenoliths of kimberlites were found. They consist of fine-grained serpentine groundmass with minute microcrysts of micas and serpentines. Xenoliths are highly calcitized and rimmed by thin micritic calcite.

Xenoliths of country rocks have not been found in this sample. Few fine-grained calcite veins cut the whole rock.

A-11 sample: HYPABYSSAL KIMBERLITE (?) (233 ft 4 inches)

Texture: almost completely homogenous, fine grained, micro-porphyritic (!), massive, unoriented (nondirectional). The sample is similar to A-10 but much finer grained and much more calcitized. Xenoliths are very small (average size 0.2 mm), while the biggest one reaches 5 mm in length.

Groundmass is the main constituent of the rock. It occupies about 40–50% of the sample volume. It consists of very fine grained mixture of serpentine minerals and minute, dispersed opaque minerals as well as abundant secondary calcite crystals and/or nests. Opaque minerals are usually much smaller than serpentine pseudomorphs. As in the A-10 sample, very often serpentine nuclei are rimmed by opaque minerals. Sometimes the nuclei are filled up with secondary calcite. The whole kimberlite is very dark green.

Micro-phenocrysts are very common (about 30–40% of the rock volume). They are represented mainly by colorless, fine-grained serpentine pseudomorphs after olivine, often showing idiomorphic contours. Majority of pseudomorphs is small (about 0.1 mm in size) and only a few are larger, up to 1 mm in diameter. Many serpentine pseudomorphs are rimmed by opaque minerals and sometimes by very fine grained serpentine. Some of them are partially or sometimes even completely filled up with fine- and/or medium- grained, secondary calcite.

Xenoliths are a not very common component of sample A-11 and occupy about 20% of its volume. Small, rounded xenoliths of kimberlites dominate. They consist of fine-grained serpentine groundmass with minute microcrysts of micas and serpentines. Some of them have distinct, emerald-green coloration. The biggest one reaches 5 mm in length and about 1 mm in width. Majority of xenoliths are highly calcitized and rimmed by thin micritic calcite rim.

Xenoliths of country rocks have not been found in this sample.

A-12 sample: TUFFISITIC KIMBERLITE (234 ft 9 inches)

Texture: similar to texture of sample A-7 but not as homogenous. To the contrary, texture of A-12 sample is more inequigranular, pseudo-conglomeratic up to pseudo-sandy, massive, and unoriented (nondirectional). Xenoliths are either well rounded or not well rounded up to 10 mm in diameter.

Groundmass occupies about 30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, opaque minerals, and secondary calcite crystals and/or nests. Small xenoliths of kimberlites and lamprophyres are also quite common within matrix.

Phenocrysts are common and occupy about 20% of the rock volume. They are represented mainly by abundant of idiomorphic serpentine pseudomorphs after olivine, often rimmed by opaque minerals. They show very distinct, net-like pattern typical for olivine serpentinization. Many serpentine pseudomorph after olivine are partially or completely replaced by secondary, fine- or medium-grained calcite. They are also rimmed by opaque minerals, which occur also within pseudomorphs, displaying characteristic, net-like pattern. Such a pattern clearly indicates primary composition of calcitized pseudomorphs (photo).

Phenocrysts of micas have not been noticed in A-12 sample.

Xenoliths of different kimberlites exceed up to 20% of the sample volume. Among them are peridotite–dunite (olivine-rich) kimberlite xenoliths as well as dark-green, lamprophyre (micaceous) xenoliths. They are spheroidal and oval in shape and differentiated in size—usually small (average size is about 1.0 mm) but a little bit larger, up to 10 mm in diameter, also occur. Xenoliths exhibit various effects of calcitization.

Xenoliths of country rocks are a common constituent of the rock and occupy up to 30% of its volume. They are represented mainly by shales, often displaying characteristic lamination and/or parallel setting of phyllosilicates (illite?). The biggest xenolith within the A-12 sample, which reaches up to 10 mm in diameter is a shale, which contain also few intercalations of aleuritc (muddy) material—mainly clasts of serpentine (?) (photo). Few shales also contain small admixture of organic material.

Besides shales few xenoliths of fine-grained and/or micritic limestones were found.

A - 13 sample: HYPABYSSAL KIMBERLITE (?) (283 ft 5 inches)

Sample A-13 is very similar to samples A-10 and A-15.

Texture: quite homogenous, fine to medium grained, porphyritic, massive, unoriented (nondirectional), typical for highly altered volcanic or subvolcanic rock. Rare xenoliths are up to 5 mm in diameter. The whole kimberlite is dark green.

Groundmass is the main constituent of the rock. It occupies about 50–60% of the sample volume and consists of very fine grained mixture of serpentine minerals, micas, opaque minerals, and secondary calcite crystals and/or nests. Opaque minerals are usually much smaller than serpentine pseudomorphs. However, in many cases serpentine nuclei is rimmed by opaque minerals.

Micro-phenocrysts are common but due to small size they occupy about 20–30% of the rock volume. They are represented mainly by colorless, fine-grained serpentine pseudomorphs after olivine, showing often idiomorphic contours. Majority of pseudomorphs is small (about 0.1 mm in size) and only few are larger, up to 1 mm in diameter. Many serpentine pseudomorphs are rimmed by opaque minerals and sometimes by very fine grained serpentine. Some of them contain various amount of secondary calcite, which sometimes forms medium- or even coarse-grained crystals.

Xenoliths are not very common component of sample A-10 and occupy not more than 20% of its volume. Only few small, rounded xenoliths of kimberlites were found. They consist of fine-grained serpentine groundmass with minute microcrysts of micas and serpentines. Xenoliths are highly calcitized and rimmed by thin micritic calcite.

Xenoliths of country rocks have not been found in this sample.

A-14 sample: ASH (PELITIC) TUFF (?) (288 ft 2 inches)

This sample completely differs from all described above samples. It is light gray, quite homogenous. Thin, about 1-mm-thick vein cuts the whole sample.

Texture: quite homogenous, fine grained (pelitic), locally with medium-grained (aleuritic) spots, massive, unoriented (nondirectional).

Groundmass is the main constituent of the rock and occupies about 60–70% of the sample. It consists of very fine grained, politic material, determination of which is very difficult under polarizing microscope. Probably it is a mixture of phyllosilicates, serpentine (?), and volcanic glass. Light-brownish pigmentation is caused by small admixture of highly dispersed, tiny opaque minerals. The composition of groundmass has to be checked by electron microprobe test, by x-ray, and/or by chemical analyses.

Detritic fraction consists of abundant of aleuritic grains (muddy fraction), among which many colorless micas, other phyllosilicates, K-feldspars, and plagioclases (!) have been recognized. Other components are too small to be distinguished with certainty.

Vein 0.1 up to 0.3 mm thick cuts the whole sample. It is filled up with hydro-micas (?), which are colorless and often form small spherolites (photo). On both sides of the vein, thin, light-brownish zones, up to 0.3 mm thick are visible. The zones, which are parallel to the vein, are enriched with very fine dispersed opaque minerals, causing brownish coloration.

This sample causes similar problem as sample T-8. It is not known if the sample represents a country rock “in situ” or if it is just a fragment of large megaxenolith, included into kimberlite. Megaxenolith is much larger than the surface of whole thin section. Thus, even any small piece of kimberlite is not visible (it is outside of thin section).

A-15 sample: HYPABYSSAL KIMBERLITE (?) (307 ft 9 inches)

Sample A-15 is very similar to samples A-10 and A-13.

Texture: quite homogenous, fine- to medium-grained, porphyritic, massive, unoriented (nondirectional), typical for highly altered volcanic or subvolcanic rock. Rare xenoliths are up to 5 mm in diameter. The whole kimberlite is dark green.

Groundmass is the main constituent of the rock. It occupies about 50–60% of the sample volume and consists of very fine grained mixture of serpentine minerals, micas, opaque minerals, and secondary calcite crystals and/or nests. Opaque minerals are usually much smaller than serpentine pseudomorphs. However, in many cases serpentine nuclei is rimmed by opaque minerals.

Micro-phenocrysts are common, but due to small size they occupy about 20–30% of the rock volume. They are represented mainly by colorless, fine-grained serpentine pseudomorphs after olivine, often showing idiomorphic contours. Majority of pseudomorphs are small (about 0.1 mm in size) and only few are larger, up to 1 mm in diameter. Many serpentine pseudomorphs are rimmed by opaque minerals and sometimes by very fine grained serpentine. Some of them contain various amount of secondary calcite, which sometimes forms medium- or even coarse-grained crystals.

Xenoliths are not very common component of sample A-10 and occupy not more than 20% of its volume. Only few small, rounded xenoliths of kimberlites were found. They consist of fine-grained serpentine groundmass with minute microcrysts of micas and serpentines. Xenoliths are highly calcitized and rimmed by thin micritic calcite.

Xenoliths of country rocks have not been found in this sample.

Appendix C—Baldwin Creek kimberlite

0’-24’9”	Casing
24’9”-29’	Drilled 4 ft 3 inches down to 29 ft. 6 inches cement then 1 ft 9 inches of kimberlite. Might have left some in the hole. Kimberlite is quite soft. It is mostly small pieces of sediment (including red shale) set in a ground mass. See ilmenite in the rock.
29’-31’	Drilled 2 ft down to 31 ft. Kimberlite as above. Possibly one larger limestone clast(?) which is loose and one shale clast about 2 inches long. Rock has several small cavities lined with calcite?
31’-36’	Drilled 5 ft to 36 ft. Kimberlite as above. Material does not drill well. It is still quite soft.
36’-39’	Drilled 3 ft recovered 3 ft 6 inches. Joe is down to 39 ft. Kimberlite looks much the same as above.
39’-40’	Drilled 1 ft recovered 7 inches. Should be at 40 ft. Drilled and recovered 9 ft of kimberlite as above. Lots of sedimentary inclusion. Also large 3–4-mm mica.
40’-59’	Recovered 9 ft 8 inches. Some of the material is washed out. Several cavities up to 1 inch. Otherwise the rock is much like above. Down to 59 ft.
59’-64’6”	Drilled and recovered 5 ft 6 inches, down to 64 ft 6 inches. Rock as above. Big phlogopite? Crystal ~4 inches from the top.
64’6”-69’	Drilled down to 69 ft. Rock as above. About halfway down one clast looks like a reworked piece. Mica (phlogopite?) is common.
69’-73’8”	Drilled ~4 ft 8 inches. Keep getting plugged up. Core breaks into small pieces and gets cock-eyed in the barrel. Some clasts are up to several inches in diameter.
73’8”-78’8”	Recovered 5 ft down to 78 ft 8 inches. Rock is still the same.
78’8”-89’	Drilled 10 ft recovered 9 ft 4 inches. Depth of hole 89 ft. No change in the rock.
89’-98’4”	Drilled 10 ft recovered 8 ft 5 inches of the same rock. Tom found a small garnet in the fine soft kimberlite. Up to now the kimberlite core breaks up very easily and appears to be quite weathered. Bottom of the core is probably 98 ft 4 inches.
98’4”-104’	Drilled 5 ft recovered 5 ft 4 inches. Total depth 104 ft. Nice-size garnet near the bottom of the hole. Rock takes on a little darker and fresher appearance. Some of the inclusions also start to look different. Also fewer cavities in this core.
104’-109’	Drilled 5 ft recovered 4 ft 9 inches. Kimberlite as above.
109’-119’	Drilled 10 ft recovered 9 ft 11 inches. Rock gets to be fresher. Best pieces of core recovered.
119’-129’	Drilled 10 ft recovered 9 ft 11 inches. Rock is relatively fresh. Still some large inclusions as well as numerous small ones. No cavities, but core shows many fractures.
129’-139’	Drilled 16 ft recovered 9 ft 1 inch. Rock as above, but there are several inclined fractures filled with gypsum(?) up to 2 mm thick.
139’-148’9”	Drilled 9 ft 9 inches recovered 10 ft 3 inhes. Core probably 148 ft 6 inches. Kimberlite same as above.
148’9”-152’1”	Drilled 3 ft 5 inches recovered 3 ft 4 inches. Kimberlite as above. Gypsum-filled fractures common. Some of the gypsum washes out during coring.
152’1”-159’	Drilled 6 ft 8 inches recovered 7 ft 2 inches. Kimberlite as above. Some different type inclusions.
159’-168’5”	Drilled 9 ft recovered 10 ft 3 inches. Joe’s depth is 168 ft. Kimberlite as above. Bottom of core 168 ft 5 inches.
168’5”-169’1”	8 ft of core measured bottom at 169 ft 1 inch. Adjust above depths.
169’1”-179’1”	Drilled and recovered 10 ft down to 179 ft 1 inch. Kimberlite has several gypsum stringers—some up to 0.5 inch thick.
179’1”-189’1”	Drilled and recovered 10 ft down to 189 ft 1 inch. Kimberlite as above.
189’1”-199’1”	Cored and recovered 10 ft down to 199 ft 1 inch. Kimberlite contains quite a few clasts that look like quartzite. Possibly from an older metamorphic terrane.
199’1”-204’4”	Drilled 5 ft 6 inches recovered 5 ft 3 inches. Drill depth 204 ft 7 inches. Kimberlite as above. Nice igneous clast at about 199 ft 6 inches.
204’4”-208’10”	Recovered 5 ft 5 inches. Measured depth 208 ft 10 inches. Core depth different. Kimberlite contains numerous gypsum veinlets at various angles. Use measured depth in core box.

208’10”-218’10” Drilled and recovered 10 ft down to 218 ft 10 inches. Kimberlite as above. Saw a garnet about 212 ft 4 inches. Gypsum veinlets at various angles common.

218’10”-228’10” Drilled and recovered 10 ft down to 228 ft 10 inches. Kimberlite as above. The rock is quite fresh and has lots of possible basement inclusions.

228’10”-238’10” Cored and recovered 10 ft down to 238 ft 10 inches. Kimberlite as above but fewer gypsum veinlets. Also a large calcite gypsum(?)-rich clast at the bottom. Several clasts that are green when wet.

238’10”-248’10” Cored and recovered 10 ft down to 248 ft 10 inches. Gypsum pocket continues for about 6 inches at the top of this core. Otherwise rock is about the same.

248’10”-258’10” Cored and recovered 10 ft down to 258 ft 10 inches. Quite a few cm-thick gypsum stringers. Otherwise the rock is as above.

258’10”-265’8” Cored 10 ft recovered 6 ft 10 inches down to 265 ft 8 inches.

265’8”-268’4” Retrieved another 2 ft 8 inches down to 268 ft 4 inches. Kimberlite is still much the same.

268’4”-278’4” Cored and recovered core down to 278 ft 4 inches. Kimberlite as above.

278’4”-287’2” Cored 10 ft recovered 8 ft 10 inches down to 287 ft 2 inches.

287’2”-288’9” Retrieved 1 ft 7 inches to 288 ft 9 inches.

288’9”-298’7” Cored 10 ft retrieved 9 ft 10 inches. Down to 298 ft 7 inches. Kimberlite as above.

298’7”-308’7” Drilled 10 ft more to give away to 308 ft 7 inches.

Appendix D—Petrology and mineralogy of the Baldwin Creek kimberlite based on thin-section examination

44’ Lots of xenoliths.consisting of shale and carbonates (~50%). Small, rounded, totally altered, possibly olivine phenocrysts, are very common. Remobilized iron colors the whole thin section and makes identification difficult. Phlogopites of different size are common but make up a small (maybe up to 1%) percentage of the rock. Opaques are common, ilmenite(?) being one, and are of different size. Groundmass of serpentine. One small garnet, just a little larger than the average olivine. No chlorites.

58’ Similar as above, but sedimentary clasts may even be larger. Resedimented material; small coarse-grained rounded clasts (olivine) within another fine-grained larger clast. We have seen the same in other sections. The clast also contains small opaque grains. Most clasts appear to have some rim around them. Good phlogopite crystal and a zircon (probe). Some muscovite with iron-rich rims.

99’ One garnet (small) (try to probe). Some phlogopite. Mostly country rock inclusions in a very fine grained groundmass. Also a feldspar (perthite) grain. Also a gypsum grain, probably secondary.

114’8” Groundmass predominates. Smaller amount of highly serpentinized olivines? Secondary calcite is common, as in other sections. Minor phlogopite, some with irregular grain boundaries. Shale and limestone clasts not as common. Some large, what appears to be serpentinized olivine crystals, that also have calcite crystals in the center.

128’ Groundmass still predominates, but more country rock xenoliths than in the last section. Many rounded serpentinized olivine crystals, some of which seem to be resedimented and enclosed in larger rounded fragments. Also large grains with most of the inside replaced by calcite. Lots of secondary carbonates. Nice, slightly radiating, phlogopite crystal (~2mm), some of which may be slightly altered to chlorite. Many small opaques.

136’4” Mostly groundmass with variable amounts of altered olivines. Some sedimentary clasts. Gypsum is also present in xenoliths. Some large serpentinized olivine grains. Small opaque minerals are common. Some phlogopites, a few are bent and in places partially altered to chlorite. Secondary calcite in porous areas or along open fractures.

142’6” Groundmass the same as above. Inclusions of different size, consisting of shale and carbonate. Two types of mica, phlogopite and biotite? Possibly some ilmenite or magnetite? (probe). Some apatite (~0.1mm), subhedral. Mica quite common. Possibly some chlorite. Elongate altered garnet crystal with a kelaphytic rim (probe).

152’8” Nice clean phlogopite (probe), but the outer edges are frayed. Maybe some of the rounded clasts are serpentinized olivines. Ilmenite and/or magnetite is present. Carbonates are again present, so is gypsum. Country rock clasts are common (shale, limestone, etc.), and mostly angular and if rounded much larger. The smaller rounded, altered fragments may be serpentinized olivines that may later be partially replaced by carbonates from the center.

159’9” Large clast of resedimented material containing numerous small, tightly packed, serpentinized olivines and one phlogopite crystal (bend). A lot of the rest of the thin section much the same, but much less tightly packed. Also numerous country rock clasts. Also gypsum clasts and numerous opaques. Also a clast or two with green chloritic material, which was possibly an amphibole or biotite? Some secondary calcite present.

172’ Lots of country rock fragments, usually angular and larger. Possibly a volcanic or subvolcanic clast. Nice large phlogopite, and a phenocryst of phlogopite in a serpentinized clast. Chlorite common. Also large serpentinized olivine with calcite in the middle. Other small olivines (serpentinized) scattered throughout the groundmass. Opaques are common. Also what looks like altered feldspars in a large clast (probe).

185’6” Similar to the last one. Groundmass with scattered serpentinized olivines as well as large, serpentinized olivines. Gypsum still very common. Some quite well preserved. Small opaques are very common. Some phlogopite, some of it bent. Country rock clasts make up ~15-20% of the rock.

191’7” Serpentine groundmass with plenty of small olivine clasts as well as resedimented clasts. Some nice, slightly altered, phlogopite. Also nice chlorite (probe). Also large olivine grains (probe microscope first) Not too many country rock clasts, mostly shale.

204’7” Most of the rock is resedimented material as well as large serpentinized olivine grains. Also more country rock clasts. Shale and limestone, some gypsum. Lots of secondary carbonates throughout. Maybe some rutile? Some phlogopite. Also nice ilmenite as well as many smaller opaques.

214’5” Similar to the last one. Lots of country rock fragments including a large breccia (carbonate) cemented by iron-oxides. Chlorite seems to be associated with this rock. Also in the last thin section, chlorite was associated with a limestone clast. Chlorites must be secondary and also associated with possible serpentinized clasts. Some phlogopite and again the greenish chloritic? mineral. A larger grain?, in which gypsum crystallizes. Rest of the grain dark brown because of Fe-overgrowth.

229’10” One part has small clasts, other part large clasts. Gypsum is common. Phlogopite is present and ilmenite. Highly serpentinized, rounded shapes were probably olivine. Altered phlogopite is not uncommon, they are big clasts.

241’10” One large (1 cm+) gypsum clast, slightly oval. Also a resedimented, tuffisitic? large clast consisting of small, closely packed, irregularly shaped, non-identifiable (serpentine) clasts. Each one of them having a rim of lighter-colored material that is also the cement. Rest of the section contains country-rock clasts, opaques and phlogopites like the former section. Also abundant gypsum.

254’7” More typical of what we have seen before. Groundmass with olivines, resedimented kimberlite and larger single olivine grains. Common country rock fragments. Lots of opaques with one large (~1 cm) ilmenite. Lots of gypsum and strained phlogopite, some of which is rimmed Fe.

266’ Not as much mica. More gypsum, but otherwise similar to the one above. Not as much carbonate, it occurs as irregular patches in the groundmass. Opaques are quite common. Also a mica from which Fe is removed to the outside and forms a rim around what is now probably muscovite.

278’8” Large amount of country rock clasts (~20%). Nice garnets (2), one with a kelaphytic ring. Different limestone clasts more common than shale. Kimberlitic material much the same as before. Gypsum here associated with a large serpentinized olivine grain and some phlogopite also. Gypsum is common. Phlogopite in resedimented clasts and in groundmass.

289’4” Similar to the last one as far as serpentinized olivine and country rock are concerned. Also rounded grain rimmed by fine-grained calcite and the center filled by gypsum. Gypsum very common throughout. Opaques common. Phlogopite also present. Opaques are common.

298’8” Many country rock fragments. Shale and limestone. Completely altered olivine grains? are common. Gypsum grains are also common and quite large (5–10%) (probe). Fe-rimmed muscovite not uncommon. Interfingering ilmenite? and phlogopite.

Appendix E—Tuttle Kimberlite on Roy Taylor’s property

4’-25’8”	Drilled to 25 ft 8 inches in kimberlite from ~4 ft. Kimberlite is clayey soft, but has some harder intervals towards the bottom. Tried to set casing (steel pipe) because we lost lots of water in the hole. Difficult to get the pipe down. Couldn’t get it down. With difficulty … got it out again. Will drill deeper with the 3-inch bit to see if we can get to harder rock, before setting casing.
25’8”-36’9”	Core ~2 ft in open hole to see what the rock looks like and whether it can be cored. No core recovery.
36’9”-56’8”	No obvious change in cuttings but the rock drills a little harder. Will try to take another core.
56’8”-58’10”	Down to 58 ft 10 inches. No core. Reamed the hole out to ~4 ft 4 inches. Set about 47 ft casing. Poured cement down to 37 ft. Cut off ~4 ft of the casing. Drilled ~16 ft of concrete down to 56 ft.
56’-62’	Cored 6 ft down to 62 ft. Recovered ~5 inches of kimberlite. Drilled down to 67 ft 6 inches. Recovered ~5 ft 10 inches of kimberlite. Recovery is fair. The rock is incompetent so that most of the core is broken up. Kimberlite has a greenish color—contains several percent mica (phlogopite?), garnet, and ilmenite. Obvious sedimentary clasts up to about 1 inch are common but make up a small percentage of the rock. The amount of small clasts is difficult to see. Some dark-brown coloration, possibly due to oxidation.
62’-77’6”	Drilled down to 77 ft 6 inches. Recovered ~5 ft 6 inches, rest is washed out. Kimberlite, about half of it broken up. One large igneous? clast several inches big. Rest looks like the kimberlite above, with lots of phlogopite. Plenty of garnet and ilmenite. Many of the clasts do not look like the typical sedimentary clasts like you see at Baldwin Creek.
77’6”-83’	Drilled 5 ft 6 inches recovered 5 ft 6 inches. Should be down to 83 ft kimberlite. Rock becomes more competent and looks like the kimberlite above.
83’-87’6”	Drilled 4 ft 6 inches recovered 4 ft 1 inch. Should be down to 87 ft 6 inches. Kimberlite as above. Several horizontal grooves near the bottom, probably caused by hard pebbles rolling around.
87’6”-97’6”	Drilled and recovered 10 ft of kimberlite. One book of phlogopite is ~3/4 inch big. Bottom is 97 ft 6 inches.
97’6”-107’6”	Drilled and recovered same kimberlite. Down to 107 ft 6 inches.
107’6”-117’6”	Drilled down to 117 ft 6 inches. Recovered 10 ft kimberlite as above.
117’6”-127’6”	Drilled 10 ft, recovered only ~6 ft 6 inches of kimberlite. Rock contains a large clast towards the bottom and large percentage of phlogopite in certain areas. Depth 124 ft should be 127 ft 6 inches.
127’6”-132’6”	Drilled 5 ft recovered 4 ft 0 inches. Depth is 132 ft 6 inches. Kimberlite as above. I think quite a bit of material gets washed out.
132’6”-137’6”	Drilled 5 ft, recovered 2 ft. Depth is 137 ft 6 inches. Poor recovery, core comes out in small pieces.
137’6”-147’6”	Drilled 10 ft recovered ~6 ft. Depth is 147 ft 6 inches. Poor recovery. Still lots of phlogopite. Some large sedimentary clasts. No obvious garnets since the phlogopite content went up.
147’6”-155’2”	Could not get the core out. Blew it out so it probably is not in the right order. Rock is much the same as above. Looks like the ilmenite as well as the garnet content is less since ~117 ft 6 inches.
155’2”-157’6”	Drilled 2 ft 4 inches down to 157 ft 6 inches. Still in quite soft micaceous kimberlite.
157’6”-167’6”	Drilled and recovered 10 ft down to 167 ft 6 inches. There are quite a few dissolution features/cavities filled with secondary minerals, but most noticeable in quite a few places, sulfides.
167’6”-177’6”	Drilled and recovered 10 ft down to 177 ft 6 inches. Core breaks apart easily and still contains sulfides in solution equities.
177’6”-187’6”	Drilled and more or less recovered 10 ft down to 187 ft 6 inches. Core is incompetent. Do not see any obvious sulfides or solution cavities in this interval. Garnets and ilmenites are absent. Much phlogopite.
187’6”-197’6”	Drilled and more or less recovered 10 ft down to 197 ft 6 inches. Kimberlite as above. Again no obvious sulfides anymore. Still a high phlogopite content.
197’6”-207’6”	Drilled 10 ft slightly better recovery of 10 ft down to 207 ft 6 inches. Possibly slightly less phlogopite. Also saw one garnet.

207’6”-217’6”	Drilled 10 ft down to 217 ft 6 inches. Alternating harder core sections containing garnets and much more friable phlogopite-rich sections that do not seem to contain garnet.
217’6”-227’6”	Drilled and recovered 10 ft to 227 ft 6 inches. The lower 3 ft is good core but contains several thin gypsum stringers. Above that the rock is alternating harder and softer. The soft areas are loaded with mica. Lower 3 ft also contains visible garnet and ilmenite.
227’6”-237’6”	Drilled and recovered 10 ft of good core down to 237 ft 6 inches. Core contains garnet, ilmenite, and a number of gypsum stringers throughout. Also large (up to several inches) sedimentary inclusions.
237’6”-247’6”	Drilled and recovered 10 ft of good core down to 247 ft 6 inches. Same as above. Also a large (several inches) clot of gypsum.
247’6”-257’6”	Drilled and recovered 10 ft of core down to 257 ft 6 inches. Much the same as above. Gypsum common. One 1 ½ inches thick layer. Also large clasts are common.
257’6”-276’6”	Drilled and recovered 10 ft to 276 ft 6 inches. Good core. Garnet and ilmenite common, one large siltstone-looking clast with possible sulfides at ~265 ft. Other interesting clasts, probably basement related, are common. Gypsum stringers also common.
276’6”-277’6”	Drilled and cored, recovered 10 ft down to 277 ft 6 inches. Rock much the same as above.
277’6”-287’6”	Drilled and recovered 10 ft down to 287 ft 6 inches. One 1 ½ inch layer of gypsum. Otherwise the rock is much the same as above.
287’6”-297’6”	Drilled 10 ft and recovered 10 ft down to 297 ft 6 inches. Kimberlite the same as above.
297’6”-307’6”	Drilled 10 ft and recovered 10 ft down to 307 ft 6 inches. Rock the same as above.

End of hole

Appendix F—Petrology and mineralogy of the Tuttle Creek kimberlite based on thin-section examination

T-l sample: TUFFISITIC KIMBERLITE (84 ft 2 inches)
Texture: inequigranular, pseudo-detrital (pseudo-conglomeratic), massive, unoriented (nondirectional), locally slightly brecciated. Xenoliths up to 12 mm in diameter.

Groundmass occupies about 20–30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, opaque minerals, and locally secondary calcite crystals and/or nests. Serpentine minerals distinctly dominate over the others. May be other minerals are also present within groundmass, but they are too fine to be recognized under polarizing microscope. Within such a groundmass abundance of very small microcrysts of serpentine, micas, chlorites, opaque minerals, phyllosilicates (?), calcite and other minerals are present.

Phenocrysts are minor component of T-l sample, not exceeding 10% of volume of the rock. They are usually rounded, ovoid, or discoidal in shape and are represented mainly by various micas up to 3 mm in size (0.2 mm in average). Among micas phlogopite dominates. Besides phlogopite also biotite and sometimes also chlorite occur.

Locally, micas show very characteristic interstratification: in one, quite large phenocryst of mica, several alternated (interdigitated) layers of phlogopite, biotite and sometimes also chlorite can be observed (photo). They differ mainly in coloration: phlogopite color varies from colorless to light brown or light green, biotite is dark brown with distinct pleochroism, while chlorite is light green with slight pleochroism. Of course other optical features are also different for the above-mentioned, particular minerals. Some mica plates (lamella) are plastically deformed (photo).

Other phenocrysts are rare and not so distinct as micas. For example, serpentine pseudomorphs after olivine are not very common in T-l sample. Moreover, it is very difficult to distinguish them from kimberlite xenoliths, which consist mainly of serpentine. This problem seems to be very important and needs additional studies.

It is also necessary to determine a strange mineral, which occurs either within groundmass or forms a nuclei of few xenoliths. It has quite distinct optical parameters: it is biaxial and shows "+" optical sign, very low birefringence (about 0.005), medium refraction indexes (about 1.6), and small angle of optical axis. These optical features are characteristic for chlorite (pennin-clinochlore suite) but microprobe test indicates unusual mica of very high content of barium. Due to uncertain results of analyses this mineral has been temporarily called mineral "X," until new data can help to determine it more precisely.

Few small grains of sphene behind any doubt belong to phenocrysts.

Opaque minerals are represented mainly by anatase highly altered to secondary ilmenite. Other opaques are chromite, magnetite, secondary hematite, and sometimes limonite. Majority of phenocrysts is rimmed by very thin layer of fine-grained serpentine probably with small admixture of phyllosilicates. Fine lamella of serpentine and or phyllosilicates are parallel to the edges (margins) of phenocrysts.

Xenoliths are the main component of the sample T-l, exceeding about 60–70 volume % of the rock. Majority of them are rounded (spherical, ovoid, discoidal and/or oval) but they differ very much in size. The average size is about 1.0 mm while the size of the largest xenolith (limestone) reaches 12 mm.

Xenoliths can be divided in two distinct types (varieties).

First type represents xenoliths of different kimberlites. They are very common (about 70% of total number of xenoliths) and usually quite small. The biggest problem with this type of xenolith is how to distinguish typical xenoliths from autholiths and from pelletal lapilli. This problem needs much more studies and discussions.

Among xenoliths of the first type the most common are light-green fragments of kimberlites, which consist of fine-grained serpentine similar to that found in matrix. Chemical composition analyzed with use of microprobe of both types of serpentines (those from matrix and those from xenoliths) is very similar. This is one more reason of big difficulties in proper recognition of kimberlites as a whole.

Majority of kimberlite (serpentine) xenoliths contain minute grains of opaque minerals and sometimes chlorites within fine-grained serpentine. They contain also small xenoliths of other serpentines, which differ slightly from serpentine, which is main component of larger xenoliths. These xenoliths are probably fragments of peridotite–dunite (olivine rich) kimberlites.

Less common, dark-green xenoliths differ from xenoliths described above by larger content of mica and chlorite microcrysts. Probably they represent fragments of lamprophyre types (micaceous) kimberlites.

Many xenoliths of both types (kimberlite and lamprophyre) have even more complicated building (setting). They have very distinct nuclei (usually phenocryst of mica or serpentine, sometimes another, smaller xenolith), which is coated with concentric layers of fine-grained serpentine. Such xenoliths can also contain microcrysts of various minerals. They represent either olivine or micaceous kimberlites, depending on the mineral composition.

Many xenoliths exhibit various effects of alteration. The most common is calcitization. Crystals of secondary calcite occur within many xenoliths. Moreover, some xenoliths are rimmed by a thin layer of fine-grained calcite.

All the described above xenoliths are undoubtedly primary phases crystallizing from kimberlite magma. Some of the clasts were used as a nucleation site, because they have overgrowths of fine-grained minerals, mainly serpentine.

Second type of xenoliths is represented by xenoliths of country rocks. They are less common than first type xenoliths, not exceeding 30% of total number of all xenoliths. Whereas, they are usually much larger. For example, the largest xenolith in T-l sample, which is limestone, reaches 12 mm in diameter.

Fine-grained and/or micritic limestones are the most common xenoliths of country rocks. Sometimes they contain highly recrystallized bioclasts or even small carbonate microorganisms like foraminifers(?), which are also highly altered.

Another variety of country rock xenoliths is shale. Shales consist mainly of very fine grained phyllosillicates (illite ?) which are usually oriented in parallel. They can contain also admixture of serpentine. In some shales small aggregates of organic matter and/or graphite are observed.
Majority of shales displays parallel lamination. Rarely they contain small, brownish spots of iron hydroxides.

Country rock xenoliths are rarely rimmed by thin layer of fine-grained calcite.

T-2 sample: TUFFISITIC KIMBERLITE (91 ft 7 inches)

Texture: very similar to texture of T-l sample (inequigranular, pseudo-conglomeratic, massive, nondirectional, locally slightly brecciated). Xenoliths up to 15 mm in diameter.

Groundmass occupies about 20–30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, opaque minerals, and locally—secondary calcite crystals and/or nests. Serpentine minerals distinctly dominate over the others. Other minerals are too fine to be recognized under polarizing microscope. Abundant of various microcrysts is also present here.

Phenocrysts are little bit more common here when compared to T-l sample, but they do not exceed 20% of the rock volume. They are very similar to those described above—usually rounded, ovoid, or discoidal in shape. Various micas (phlogopite, more rarely biotite and sometimes also chlorite) dominate. Characteristic interstratification as well as mica plates deformation are quite common. Small, rare inclusions of zircons produces black halos around surrounding biotite (photo).

Serpentine pseudomorphs after olivine are not very common in T-2 sample and cause the same problem with identification as in sample T-l. Sphene has not been observed here.

Whereas few large phenocrysts of garnets occur within T-2 sample, one of them reaches 8 mm in diameter and is situated within large (15 mm in diameter) xenolith of dark, micaceous kimberlite (lamprophyre). Microprobe analysis shows that it is a pirope (fig.). It has very narrow rim of "kelyphite." Another garnet, located in very small xenolith of kimberlite is much smaller (about 2 mm in diameter) and has quite wide rim of "kelyphite." The "kelyphite" comprises a micro-crystalline, optically irresolvable aggregate of phyllosilicates and spinels (photo).

Opaque minerals form usually small, idiomorph crystals filled up with secondary ilmenite with some relics of primary anatase (photo). Other opaques represent chromite, magnetite and secondary hematite and sometimes limonite.

Mineral "X" is not common here.

Xenoliths are the main component of the sample T-2, exceeding about 50–60 volume % of the rock. They are quite similar to xenoliths from sample T-l. Their average size is about 1.0 mm while the size of the largest xenolith (micaceous kimberlite) reaches 15 mm.

As in the sample T-l xenoliths can be divided in two distinct types (varieties). First type represents xenoliths of different kimberlites. They are very common but usually quite small. Light-green xenoliths are probably fragments of peridotite–dunite (olivine rich) kimberlites. Less common, larger (up to 15 mm), dark-green xenoliths probably represent fragments of lamprophyre-type (micaceous) kimberlites.

Xenoliths of both types have sometimes distinct nuclei (usually phenocryst of mica or serpentine, sometimes another, smaller xenolith), which is coated with concentric layers of fine-grained serpentine. Such xenoliths can also contain microcrysts of various minerals. Many of all types of xenoliths exhibit some effects of calcitization.

Few kimberlite xenoliths are filled up with a combination of calcite, phlogopite and perovskite—products of metasomatization of primary serpentine (photo).

Xenoliths of country rocks do not exceed 10% of the total volume of xenoliths. They are usually quite small and are represented mainly by fine-grained and/or micritic limestones, sometimes with small shadows of highly altered bioclasts and microorganisms. Another type of country rock xenoliths are shales showing sometimes parallel lamination. Country rock xenoliths are rarely rimmed by a thin layer of fine-grained calcite.

Many xenoliths exhibit various effects of calcitization.

The whole rock contains various amount of secondary calcite, which either forms isolated grains or aggregates and/or small nests.

This sample is a typical representative of one from two distinct types of kimberlites. Therefore, it has been analyzed with electron microprobe. Hitherto obtained results of microprobe tests are presented in last chapter "Summary."

T-3 sample: TUFFISITIC KIMBERLITE (97 ft 2 inches)

Texture: very similar to texture of the samples described above (inequigranular, pseudo-conglomeratic, massive, non-directional, locally slightly brecciated). Xenoliths up to 20 mm in diameter.

Groundmass (up to 30% of the rock sample volume) consists of very fine grained mixture of serpentine minerals, opaque minerals, and locally—secondary calcite crystals and/or nests.

Serpentine dominates. Abundant of various microcrysts is also present here.

Phenocrysts do not exceed 10% of the rock volume. They are very similar to those described in T-2 sample—usually rounded, ovoid, or discoidal in shape. Various micas (phlogopite, more rarely biotite, and sometimes also chlorite) dominate. Serpentine pseudomorphs after olivine are not very common here. Few, rather small phenocrysts of garnets also occurred within xenolith of dark, micaceous kimberlite (lamprophyre).

Garnets have narrow rims of "kelyphite." Opaque minerals are represented mainly by anatase highly altered to secondary ilmenite. Other opaques are chromite, magnetite, secondary hematite, and sometimes limonite. Mineral "X" is not common here.

Xenoliths are the main component of T-3 sample, exceeding about 60–70 volume % of the rock. They are quite similar to xenoliths from samples T-l and T-2. Their average size is about 1.0 mm while the size of the largest xenolith (altered micaceous kimberlite) reaches 20 mm.

Xenoliths of different kimberlites (peridotite–dunite and lamprophyre) are not very common here. They do not exceed 20% of the total number of xenoliths. They sometimes have distinct nuclei, coated with concentric layers of fine-grained serpentine. Such xenoliths can also contain microcrysts of various minerals. Many of all types of xenoliths exhibit some effects of calcitization.

The biggest xenolith in sample T-3 has more than 20 mm in diameter. It is dark-greenish-brown, highly altered, micaceous kimberlite xenolith. It consists of many small phenocrysts of micas, chlorites, opaque minerals, and garnets as well as other micro-xenoliths set within altered, fine-grained groundmass. Dark appearance resulted from products of alteration: phyllosilicates, chlorites, opaque minerals, and so on. Phenocryst of garnet is relatively large and it is rimmed with kelyphite.

Xenoliths of country rocks dominate over others, reaching up to 80% of the total volume of xenoliths. They are usually quite small and are represented mainly by fine-grained and/or micritic limestones, sometimes with small shadows of highly altered bioclasts and microorganisms. Only one micritic calcite xenolith is larger, having a size of 15 mm. Other country rock xenoliths are shales showing very often distinct parallel lamination. Country rock xenoliths are rarely rimmed by thin layer of fine-grained calcite.

Many xenoliths exhibit various effects of calcitization.

The whole rock contains various amount of secondary calcite, which either forms isolated grains or aggregates and/or small nests.

T-4 sample: TUFFISITIC KIMBERLITE (161 ft)

Texture: very similar to texture of the samples described above (inequigranular, pseudo-conglomeratic, massive, nondirectional, locally slightly brecciated). Xenoliths up to 20 mm in diameter.

Groundmass occupies about 20–30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, opaque minerals, and locally—secondary calcite crystals and/or nests. Serpentine minerals distinctly dominate over the others. Abundant of various microcrysts is also present here.

Phenocrysts do not exceed 10% of the rock volume—usually rounded, ovoid, or discoidal in shape. Various micas (phlogopite, more rarely biotite, and sometimes also chlorite) dominate. Characteristic interstratification as well as mica-plate deformation are quite common.

Serpentine pseudomorphs after olivine are not common here. Opaque minerals are similar to these described above. Mineral "X" is not common here.

Xenoliths are the main component of the sample T-4, exceeding about 60–70 volume % of the rock. They are spheroidal and oval in shape and very differentiated in size (average size is about 1.0 mm while the size of the largest xenolith (micaceous pyroxene lamprophyre) reaches 20 mm.

Xenoliths of different kimberlites are quite common here. They are peridotite–dunite (olivine-rich) kimberlite xenoliths as well as less common, dark-green, lamprophyre-type (micaceous) xenoliths.

Xenoliths of both types often have quite distinct nuclei (usually phenocryst of mica or serpentine, sometimes another, smaller xenolith), which is coated with concentric layers of fine-grained serpentine. Such xenoliths can also contain microcrysts of various minerals and very small microxenoliths of other kimberlites.

One particular xenolith is worth being described separately. It is the largest xenolith within the T-4 sample (more than 20 mm in diameter). It represents a fragment of micaceous pyroxene lamprophyre. Within a fine-grained serpentine groundmass, it contains many phenocrysts of light-brown biotite and a similar amount of dark-bottle-green chromiferous diopside (photo). Mafic minerals form few delicate lamina. Due to the quite large size and lack of alterations, it was possible to carefully check optical data of all mineral components of this particular xenolith, for example the angle of extinction (z/_) of diopside equals 40°.

Many xenoliths exhibit various effects of calcitization.

Xenoliths of country rocks are also quite common here, exceeding about 50% of the total volume of xenoliths. They are usually quite small (about 2 mm in average) and are represented mainly by fine-grained and/or micritic limestones, sometimes with shadows of highly altered small bioclasts and microorganisms.

Another type of country rock xenoliths are shales, which sometimes show parallel lamination. One of them reaches 15 mm in diameter and besides phyllosilicates contains small admixture of organic matter (graphite), which causes very dark coloration of this xenolith.

Either the whole rock or particular xenoliths contain various amount of secondary calcite, which either forms isolated grains or aggregates and/or small nests.

Sample T-4 is very interesting and has been choose for the next electron microprobe test. A small sample has already been given to the laboratory in order to make special preparation.

T-5 sample: TUFFISITIC KIMBERLITE (210 ft 9 inches)

Texture: very similar to texture of the samples described above (inequigranular, pseudo-conglomeratic, massive, nondirectional, locally slightly brecciated). Xenoliths up to 12 mm in diameter.

Groundmass occupies about 20–30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, opaque minerals, and locally—secondary calcite crystals and/or nests. Serpentine minerals distinctly dominate over the others. Abundant of various microcrysts is also present here.

Phenocrysts are quite common here (about 15% of the rock volume)—usually rounded, ovoid, or discoidal in shape. Various micas (phlogopite, more rarely biotite, and sometimes also chlorite) dominate. Characteristic interstratification as well as mica-plate deformation are quite common. Besides micas, also few low-Cr diopside phenocrysts are present here. One quite large phenocryst of diopside is included in ovoid kimberlite xenolith. It is rimmed with kelyphite in a way that the inner part of diopside is absolutely fresh, colorless, while external part is replaced by dark, fine-grained mixture of phyllosilicates(?), perovskite ,and opaques. The angle of extinction (z/_) of diopside equals 34°. Opaque minerals are similar to these described above. Serpentine pseudomorphs after olivine and mineral “X” are not common here.

Xenoliths are the main component of the sample T-5, exceeding about 60–70 volume % of the rock. They are spheroidal and oval in shape and very differentiated in size (average size is about 1.0 mm while size of the largest xenolith [limestone] reaches 12 mm).

Xenoliths of different kimberlites are quite common here. They are peridotite–dunite (olivine-rich) kimberlite xenoliths as well as less-common, dark-green, lamprophyre-type (micaceous) xenoliths.

Xenoliths of both types have quite often distinct nuclei (usually phenocryst of mica or serpentine, sometimes another, smaller xenolith), which is coated with concentric layers of fine-grained serpentine. Such xenoliths can also contain microcrysts of various minerals and very small microxenoliths of other kimberlites.

One small kimberlite xenolith shows locally trachitic texture picked up by lath-shaped crystals of calcite (?).

Many xenoliths exhibit various effects of calcitization.

Xenoliths of country rocks are also quite common here, exceeding about 40% of the total volume of xenoliths. They are usually quite small (about 2 mm in average) and are represented mainly by fine-grained and/or micritic limestones, sometimes with shadows of highly altered small bioclasts and microorganisms. One fragment of micritic limestone is the biggest within T-5 sample and reaches 12 mm in diameter.

Other country rock xenoliths are shales composed of clay minerals, locally enriched with small admixture of organic matter. Shales show sometimes parallel lamination.

Either the whole rock or particular xenoliths contain various amount of secondary calcite, which forms isolated grains or aggregates and/or small nests.

T-6 sample: TUFFISITIC KIMBERLITE BRECCIA (225 ft 10 inches)

Texture: quite similar to texture of the samples described above; however, some clasts are less rounded and more brecciated. Xenoliths are up to 15 mm in diameter.

Groundmass occupies about 20–30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, opaque minerals, and locally—secondary calcite crystals and/or nests. Serpentine minerals distinctly dominate over the others. Abundance of various microcrysts is also present here. Groundmass contains also small admixture of secondary phyllosilicates (hydromicas?), products of primary minerals alteration.

Phenocrysts do not exceed about 15% of the rock volume. They are usually rounded, ovoid, or discoidal in shape. Various micas (phlogopite, more rarely biotite, and sometimes also chlorite) dominate. Mica plates often show characteristic interstratification as well as deformation. Serpentine pseudomorphs after olivine are quite common here. Besides micas and serpentine also few low-Cr diopside phenocrysts are present here. The angle of extinction (z/_) of diopside equals 55°. The crystals of diopside are often rimmed by kelyphite. Main part of some crystals is altered into opaque minerals (photo). Other opaque minerals, similar to these described earlier, are dispersed within groundmass or xenoliths. Mineral “X” is quite common in T-6 sample. It fills up thin vein, which cuts the whole sample. Moreover, it often forms nuclei within many kimberlite xenoliths and locally forms relatively large crystals. It helped to conduct one more optical test, which confirmed previously obtained data. This biaxial mineral shows “+” optical sign, very low birefringence (about 0.005), medium refraction indexes (about 1.6), and small angle of optical axis. These optical features are characteristic for chlorite (pennin–clinochlore suite) but preliminary result of microprobe test indicates that it is unusual mica of very high content of barium.

Xenoliths are the main component of the sample T-6, exceeding about 60–70 volume % of the rock. Besides spheroidal and oval many angular xenoliths occur. They are very differentiated in size (average size is about 1.0 mm while size of the largest xenolith [micaceous lamprophyre] reaches 15 mm).

Xenoliths of different kimberlites are quite common here: dark-green lamprophyre-type (micaceous) xenoliths as well as less common peridotite-dunite (olivine-rich) kimberlite xenoliths. The biggest xenolith reaches 14 mm in diameter and has very angular shape with sharp edges. Within dark, brownish-black groundmass full of minute opaque minerals, it contains numerous microphenocrysts of micas (phlogopite and biotite) and other minerals, highly calcitized or altered to opaques. This xenolith seems to be a fragment of micaceous lamprophyre. Another dark xenolith contains (besides the components described above) relatively large phenocryst of diopside, partially replaced by opaque minerals and other products of alteration (photo).

Many xenoliths exhibit various effects of calcitization

Xenoliths of country rocks are not very common here, exceeding about 30% of the total volume of xenoliths. They are usually quite small (about 2 mm in average) and are represented mainly by fine grained and/or micritic limestones. One of them contains abundant of microorganisms (among the others—foraminifers) (photo). Another country rock xenoliths are shales composed of clay minerals, sometimes showing parallel lamination.

Either the whole rock or particular xenoliths contain various amount of secondary calcite, which either forms isolated grains or aggregates and/or small nests.

Sample T-6 is very interesting and has been chosen for the next electron microprobe test. Small sample has already been given to the laboratory in order to make special preparation.

T-7 sample: TUFFISITIC KIMBERLITE (248 ft 11 inches)

Texture: very similar to texture of the samples described above (T-l to T-5) (inequigranular, pseudo-conglomeratic, massive, nondirectional, locally slightly brecciated). Xenoliths are up to 15 mm in diameter.

Groundmass occupies about 20–30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, opaque minerals, and locally—secondary calcite crystals and/or nests. Serpentine minerals distinctly dominate over the others. Abundant of various microcrysts is also present here.

Phenocrysts are quite common here (about 15% of the rock volume). Various micas (phlogopite, more rarely biotite, and sometimes also chlorite) dominate. Characteristic interstratification as well as mica-plate deformation are quite common. Besides micas also few low-Cr diopside phenocrysts are present here. Serpentine pseudomorphs after olivine and mineral “X” are not common here.

Xenoliths are the main component of the sample T-7, exceeding about 60–70 volume % of the rock. Xenoliths of different kimberlites are quite common here. They are dark-green, lamprophyre-type (micaceous) xenoliths as well as less common peridotite–dunite (olivine-rich) kimberlite xenoliths. They are spheroidal and oval in shape and very differentiated in size (average size is about 1.0 mm while size of the largest xenolith [micaceous lamprophyre] reaches 15 mm). One rather small, dark xenolith of lamprophyre contains mainly mica microcrysts as well as one microcryst of highly altered plagioclase with relics of parallel, slightly deformed, multiple twinning (photo).

Many xenoliths exhibit various effects of calcitization.

Xenoliths of country rocks dominate over other xenoliths, exceeding about 60% of their total volume. They are usually quite small (about 2 mm in average) and are represented mainly by shales composed of clay minerals and sometimes showing parallel lamination.

Other common country rock xenoliths are fine-grained and/or micritic limestones. Xenoliths of organogenic limestones containing shadows of highly altered small bioclasts and microorganisms are very rare.

Either the whole rock or particular xenoliths contain various amount of secondary calcite, which forms isolated grains or aggregates and/or small nests.

T-8 sample: MICRODIORITE Z (264 ft)

Sample completely different from all samples described up to now. Hand specimen is very dark bluish-black, fine crystalline, homogenous.

Texture: holocrystalline, fine- to medium-grained, granulometric, massive, nonoriented (however, locally delicate parallel lamination is visible), hipidiomorphic, micro-gabbroid.

Mineral composition: mafic minerals are in equilibrium with leucocratic ones. Among mafics brown hornblende slightly prevails over clinopyroxene (augite). Very small amount of olivine is also present. The angle of extinction (z/_) of augite, measured perpendicularly to nβ, equals 38°, while the angle of extinction (z/_) of hornblende equals 25°.

Leucocratic minerals are represented mainly by plagioclases (oligoclase–andesine). Very often they exhibit normal zonal setting (andesine in the core, while oligoclase outside). Small amount (not more than 10% of the rock volume) of microcline is also present.

Such a mineral composition as well as texture of the rock is very typical for hypabyssal diorite. However, it is not possible to ascertain if this particular sample represents regular hypabyssal rock or if it is just a very large xenolith within kimberlite. In the latter case kimberlite itself could not be visible, because the size of diorite fragment surpasses the size of the whole thin section.

T-9 sample: TUFFISITIC KIMBERLITE (beautiful!) (265 ft 8 inches)

Texture: very similar to texture of the samples described above (excluding T-6 and T-8) (inequigranular, pseudo-conglomeratic, massive, nondirectional, locally slightly brecciated). Xenoliths are up to 25 mm in diameter.

Groundmass occupies about 20–30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, opaque minerals, and locally—secondary calcite crystals and/or nests. Serpentine minerals distinctly dominate over the others. Abundant of various microcrysts is also present here.

Phenocrysts are very common here (about 30% of the rock volume). Various micas (phlogopite, more rarely biotite and sometimes also chlorite) predominate. Characteristic interstratification as well as mica-plate deformation are very common. Some mica plates reach 8 m in length and 2 mm in width. Mineral "X" is also common here. Besides micas and "X" also few small garnets with kelyphite rims are present here.

The nicest and biggest phenocryst (up to 25 mm in diameter) is serpentine pseudomorph after olivine. It shows characteristic net-like pattern and contains abundant of small acicular crystals of opaque minerals of parallel and/or concentric setting (photo). Locally, large serpentine pseudomorph contains small, irregular intergrowths of "X" mineral.

Xenoliths are the main component of the sample T-9; however, they do not exceed 40 volume % of the rock. Among them xenoliths of different kimberlites dominate. They are dark-green lamprophyre-type (micaceous) xenoliths as well as less common peridotite–dunite (olivine-rich) kimberlite xenoliths. They are spheroidal and oval in shape and rather small (average size is about 1.0 mm).

Many xenoliths exhibit various effects of calcitization.

Xenoliths of country rocks are very rare, exceeding about 20% of total volume of xenoliths. They are usually small (about 2 mm in average) and are represented mainly by fine-grained and/or micritic limestones and less often by clayey shales, showing sometimes parallel lamination.

Either the whole rock or particular xenoliths contain various amount of secondary calcite, which forms isolated grains or aggregates and/or small nests.

Sample T-9 is very interesting and has been chosen for the next electron microprobe test. Small sample has already been given to the laboratory in order to make special preparation.

T-10 sample: TUFFISITIC KIMBERLITE (299 ft 8 inches)

Texture: very similar to texture of the samples described above (excluding T-6 and T-8) (inequigranular, pseudo-conglomeratic, massive, nondirectional, locally slightly brecciated). Xenoliths are up to 10 mm in diameter.

Groundmass occupies about 20–30% of the rock sample volume. It consists of very fine grained mixture of serpentine minerals, opaque minerals, and locally—secondary calcite crystals and/or nests. Serpentine minerals distinctly predominate over the others. Abundant of various microcrysts is also present here.

Phenocrysts are not common here (about 10% of the rock volume). Various micas (phlogopite, more rarely biotite and sometimes also chlorite) dominate. Characteristic interstratification as well as mica-plate deformation are quite common. Serpentine pseudomorphs after olivine and mineral "X" are rare.

Xenoliths are the main component of the sample T-10, exceeding about 50–60 volume % of the rock. Xenoliths of different kimberlites are quite common here. They are mainly peridotite-dunite (olivine-rich) kimberlite xenoliths as well as less-common dark-green, lamprophyre (micaceous) xenoliths. They are spheroidal and oval in shape and very differentiated in size (average size is about 1.0 mm while size of the largest xenolith [micaceous lamprophyre] reaches 10 mm).

One of the most interesting xenoliths is a fragment of a micro-diorite, which is very similar to the one described as T-8 sample. It contains abundance of relatively small crystals of brown hornblende (photo) set within a mass of highly altered plagioclases. Proportion of hornblende to clayey pseudomorphs after plagioclases is close to 50%. This micro-diorite represents less abyssal facie than T-8 sample and is much more altered. Size of micro-phenocrysts shows that it is fragment of a subvolcanic rock.

Another distinct, quite large (up to 10 mm in diameter) xenolith is a fragment of fine-grained micaceous lamprophyre. It contains discoidal nuclei of fine-grained serpentine (probably kimberlite xenolith).

Many xenoliths exhibit various effects of calcitization.

Xenoliths of country rocks dominate over other xenoliths, exceeding about 60% of their total volume. They are usually quite small (about 2 mm in average) and are represented by similar amount of clayey shales and fine-grained and/or micritic limestones.

Either the whole rock or particular xenoliths contain various amount of secondary calcite, which forms isolated grains or aggregates and/or small nests. Numerous xenoliths and phenocrysts are almost completely replaced by fine and/or medium crystalline calcite. Calcite pseudomorphs are often rimmed by thin layer of opaque minerals (photo), showing contours of primary minerals.

Thin vein of mineral "X" is visible along one of the edges of the sample. Small crystals of mineral "X" are perpendicular to the edge.