PETROLOGY OF THE
LEONARDVILLE KIMBERLITE

by

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B. S., OLD DOMINION COLLEGE, 1967

3735

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Geology

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1970

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INTRODUCTION

Statement of Problem

This investigation is but part of a long term project undertaken by Dr. D. G. Brookins and the Department of Geology to investigate fully the nature of the six known kimberlites in Riley County, Kansas, and to therefore learn more about the earth's upper mantle and the mechanism (s) of kimberlite emplacement.

The Leonardville kimberlite was chosen for investigation because it has been subject to very little prior work. It is hoped that this work will be a worthwhile addition to the Department's program.

Of necessity this thesis is limited, but the author hopes that this work can lead to more significant contributions.

Geologic Setting

The Leonardville kimberlite is one of six kimberlites in Riley County, Kansas. Five crop out in the upper Chase Group, Gearyan Stage, Lower Permian Series of the Permian System which consists of beds of shale, carbonate rocks and a few sandstones. The Leonardville kimberlite crops out in the Winfield Limestone, which is the uppermost formation of the Chase Group, at $SE\frac{1}{4}$ $NE\frac{1}{4}$ Sec. 22, T8S, R5E. The outcrop forms a slight topographic high of about five feet on the flank of a long, gently sloping hill with a relief of no more than 40 feet (Fig. 1). The outcrop area is roughly oval, having axes of 100 feet and 60 feet.

The main structural feature, to which the kimberlites of Riley County may be related, is the Abilene Anticline (see Fig. 2). The magnetic trends of the kimberlites, although somewhat different from one another, are all approximately perpendicular to the axis of this anticline. The probability of this being a

EXPLANATION OF FIGURE 1

Topographic and magnetic contour map of the Leonardville
kimberlite site (modified from Cook, 1955).

Figure 1.

Leonardville
Kimberlite

0   100   200   300
feet   N

FENCE

OUTCROP

1005
1000
995
1000
995
990
985
980
975

Contour Interval
Five Feet
Magnetic contours, broken
lines, at 500 gammas
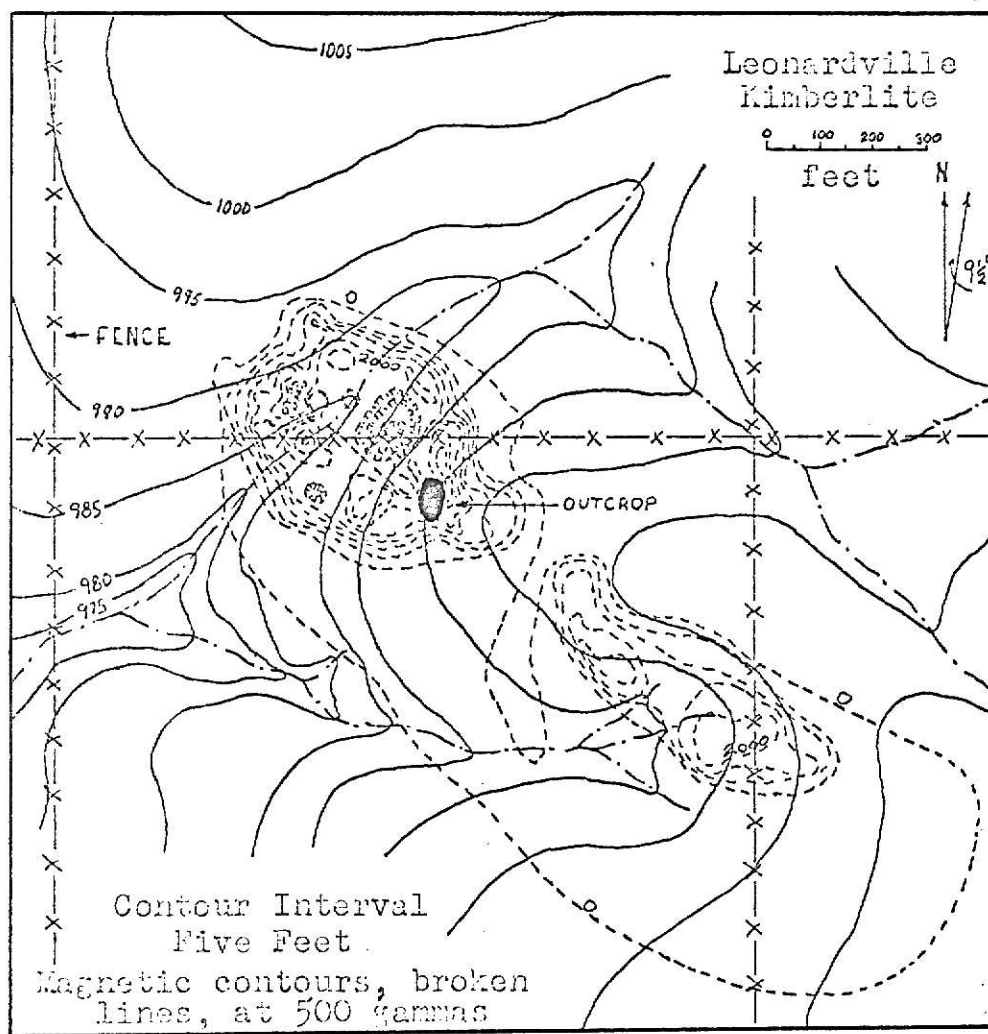
EXPLANATION OF FIGURE 2

Map of Riley County, Kansas showing the location of
structure (Shenkel, 1959), and igneous intrusions.

1. Bala Intrusion   4. Randolph No. 1 Intrusion

2. Leonardville Intrusion   5. Randolph No. 2 Intrusion

3. Stockdale Intrusion

Figure 2

LEGEND

↕ ANTICLINE AXIS

⚹ SYNCLINE AXIS

○ IGNEOUS INTRUSION OR CRATER

＼ MAGNETIC TREND

SCALE

0 1 2 3 4 5 MILES

R.4E. R.5E. R.6E. R.7E.

T.6S.

T.7S.

T.8S.

T.9S.

T.10S.

T.11S.

R.8E. R.9E.

WINKLER

RANDOLPH

LEONARDVILLE

BALA

RILEY

FORT RILEY
MILITARY
RESERVATION

MANHATTAN

OGDEN
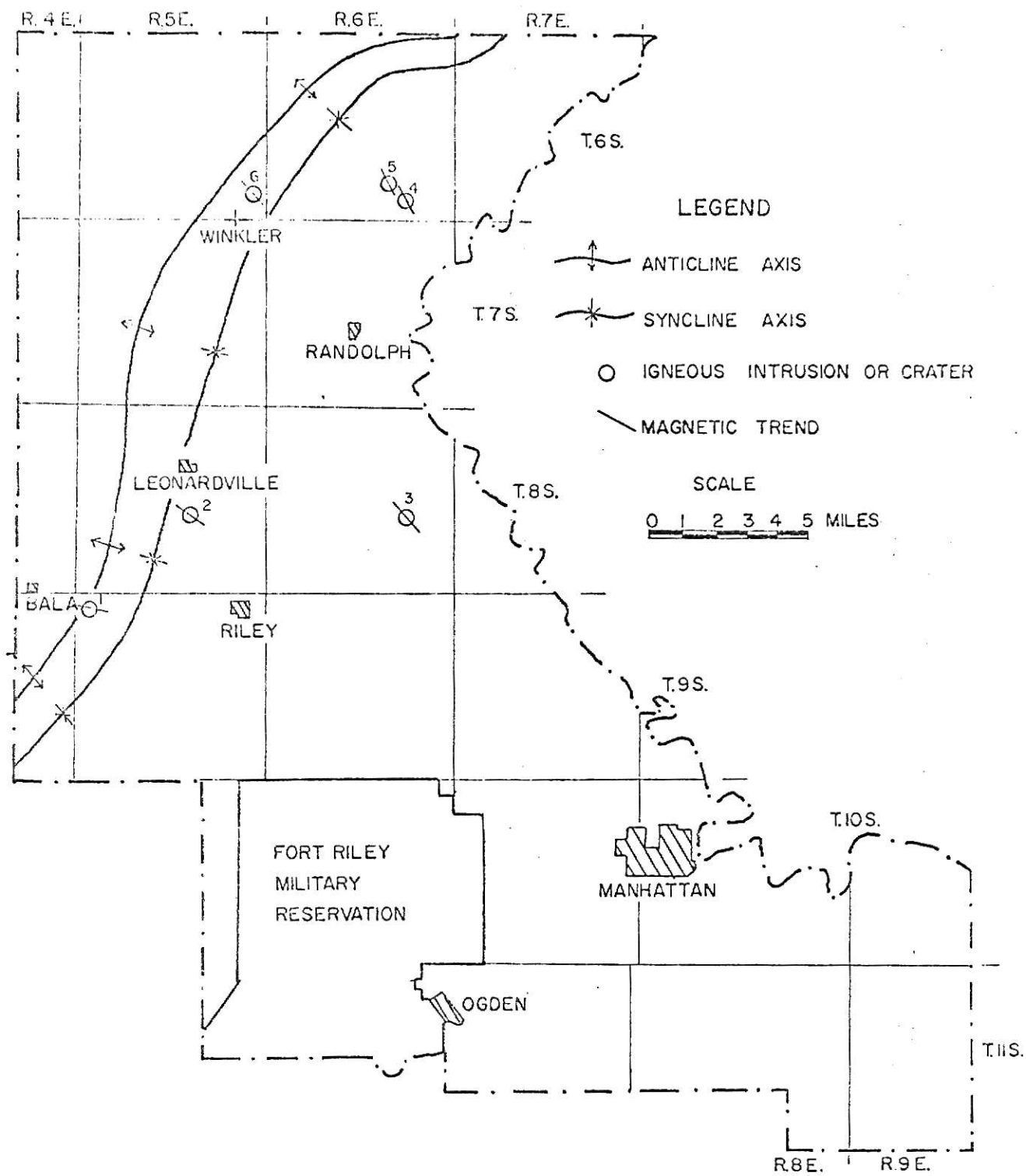
random event is unlikely and therefore a relationship between the kimberlites and the Abilene Anticline is assumed.

Physiographically Riley County is in the northern-most portion of the Flint Hills Upland, Osage Plains of the Central Lowland division (Fenneman, 1946).

Previous Work

The discovery dates of the Stockdale and Bala kimberlites are not known but their existence has been known for at least 100 years. Moore and Haynes (1920) in a discussion of basic igneous outcrops in Kansas, mentioned that in 1871 the Bala kimberlite had been mined in an attempt to recover copper. An oral paper was read before the Kansas Academy of Science concerning the "basic igneous rocks" of Kansas by Sperry (1929). Tolman and Lander (1939) cite A. B. Sperry's discovery of the Leonardville kimberlite in 1935. Jewett (1941) gave the location and a brief description of three of the six kimberlites in Riley County. Dreyer (1947) presented a magnetic and structural study of the Bala kimberlite. In 1955 Cook published a magnetic study of five of the kimberlites and concluded that they persist at depth and that they all are vertical or steeply dipping to the southeast. Byrne, Parish and Crumpton (1956) summarized the locations and the descriptions of five of the kimberlites. Shenkel (1959) discussed the geology of the Abilene Anticline.

Eastwood and Brookins (1965) proposed a possible maximum injection temperature of 400° to $550^\circ C$ and a sequence of mineral crystallization for the Stockdale and Bala kimberlites based upon a spectrochemical investigation. They also concluded that both kimberlites were differentiated from a parent magma and from each other and that both acted as closed systems. Later work by Brookins (1969b) revised the temperature of injection down to 75° to $150^\circ C$. Rosa and Brookins

(1966) investigated the mineralogy of the Stockdale kimberlite by petrographic and x-ray diffraction methods. Brookins (1969b) presented K-Ar dates on phlogopite from the Stockdale and Leonardville kimberlites. Dyer and Brookins (1969) presented a preliminary discussion of the mineralogy and petrography of the Leonardville kimberlite. Brookins (1967a) also studied the strontium geochemistry of the Bala and the two Randolph kimberlites, and summarized the general features of five of the kimberlites (1967b). A high chromium pyrope (7.90% Cr_2O_3) from Stockdale reported by Bagrowski (1941) was re-examined by Brookins (1967c) and was found to contain 2.77% Cr_2O_3.

A sixth kimberlite has been discovered by drilling the Winkler Crater in northern Riley County. Brookins (1970) has begun preliminary investigation of the kimberlite and the meager data collected thus far indicate that the rock is very similar to the Stockdale and Leonardville kimberlites.

Unpublished work regarding the kimberlites and related geologic features is largely confined to thesis investigations at Kansas State University. Neff (1949) studied the joint patterns in Riley County. Taylor (1950) investigated the structural relations of the kimberlites relative to the Abilene Anticline and suggested a north-south trending strike-slip fault in the basement complex with associated "gash fractures" through which the kimberlites were intruded. Nelson (1952), in his study of the basement complex of Riley and Marshall Counties, related the kimberlites to the joint pattern in Riley County. Bridge (1953) presented a petrographic and petrologic study of the Riley County kimberlites. He concluded, based on "most of the samples" coming from the Stockdale kimberlite, that they were originally pyroxenites or pyroxenite differentiates of a gabbroic magma. Further, Bridge felt that serpentinization began before emplacement and was due to internal water which also acted as a lubricant during emplacement. Dowell (1964) compiled a magnetic survey of five

of the kimberlites and confirmed the findings of Cook (1955). Eastwood (1965) made a spectrochemical investigation of the Bala and Stockdale kimberlites. Rosa (1966) studied the mineralogy and petrogenesis of the Stockdale kimberlite. McDermott (M. S. Thesis in progress...) is working on the petrography and mineralogy of the Randolph kimberlites.

<center>Kimberlites</center>

Kimberlites are interesting rocks from several points of view: (1) economically they can be rather valuable as they and some of their ultrabasic inclusions are the only known primary source of terrestial diamond, (2) they are extremely rare rocks, and (3) their origin and emplacement histories are poorly understood.

Initial interest in kimberlite stemmed from the discovery of diamonds in the South African occurrences. The name kimberlite was taken from the Kimberly mine where the diamonds were initially discovered. The type specimen was described by Lewis (1887) as a diamondiferous mica peridotite. Most workers today no longer require diamond as a necessary constituent before a rock is termed a kimberlite because several other types of rocks are chemically and petrologically similar. A kimberlite then, may be defined as a partially or wholly serpentinized and/or carbonated mica peridotite, with or without garnet, containing inclusions of country rocks and sometimes ultramafic rocks such as eclogite and pyroxenite.

Kimberlites are classed as (1) massive kimberlite, (2) intrusive kimberlite breccia, and (3) kimberlite tuff or tuff Breccia. Massive kimberlite, containing few or no inclusions, consists of a "basaltic" type with a dominance of olivine or serpentized olivine, or a "micaceous" variety in which mica forms more than five percent of the mineral grains. Intrusive kimberlite breccias consist of from 20 to 60 percent inclusions that are country rocks or kimberlite fragments.

The inclusions are enclosed in a massive kimberlite matrix. Kimberlite tuff, or tuff breccia contains more than 60 percent inclusions, lacking a matrix, that are cemented by hydrothermal minerals (Dawson, 1967).

Many petrologists believe that the ultramafic inclusions in kimberlite are from upper mantle or are early melting fractionations of a garnet-peridotite (O'Hara and Yoder, 1967). An alternative hypothesis, although not popular, is that the ultramafic inclusions are derived from metamorphic terrains deep within the crust (Davidson, 1967).

Aside from containing diamonds, the chemistry of kimberlites sets them apart from other rocks. One major feature is the degree of silica undersaturation. A resonable figure for the world average of kimberlites might well be 30 percent SiO_2 (see table 1 for some comparisons). For a rock of such low silica content, kimberlites have anomalously high amounts of Ti, Al, Ca, K, P, S, CO_2 and fixed water. They also have a low Mg/Fe ratio but high K/Na and Fe^{+3}/Fe^{+2} ratios. Li, B, Sc, V, Cu, Ga, Rb, Sr, Y, Zr, Cs, Nb, Ba, La, Ta and Pb occur in amounts generally higher than other low silica igneous rocks.

Daly (1933, p. 378) estimated that "the total volume of known kimberlite is less than that of a granite stock of moderate size". No doubt that estimate has been doubled or tripled since 1933, particularly since the Russians have been vigoriously exploring for a domestic diamond. Their efforts have born fruit. As of 1964, hundreds of kimberlite dikes and pipes had been discovered throughout the Siberian platform, enabling the Russians to account for about an eighth of the total world production of diamonds (Davidson, 1967).

Of the origin and emplacement of kimberlite there is little agreement among kimberlite devotees. Opinions regarding origin range from primary kimberlite magmas to complex mixtures of kimberlite with other pre-existing rocks. The several hypotheses concerning emplacement show somewhat more agreement. It

is generally agreed that an initial stage involves an explosive phase (gas charged magma), followed by a slow to rapid upwelling of a well lubricated crystal "mush" along zones of weakness, abrading and rounding mineral grains and inclusions. Lack of pyrometamorphism of wall rocks suggest low (200-300°C) intrusion temperatures, (Dawson, 1967; Brookins, 1969b).

Dawson (1967) advocates that kimberlite rock is formed by assimilation of granite by a H_2O-rich ankeritic carbonatite magma. This hypothesis goes a long way to explain the unusual chemistry of kimberlites but Dawson does not present any discussions regarding the origin of the carbonatite magma.

O'Hara and Yoder (1967) concluded that kimberlite groundmass is a late stage accumulate formed by partial melting and successive fractionation of a garnet peridotite. Rickwood, et al (1968) have adopted the same conclusion.

Some petrologists regard kimberlite groundmass as strongly altered melilite basalt (Heinrich, 1966). However, recent work (Yoder, 1968, p. 476) restricts "olivine melilite 'basalt'" to depths equivalent to those within the continental crust in the presence of an excess of water [and therefore] casts some doubt on the concept that the magmatic portion of kimberlite is hydrothermally altered melilite basalt magma".

Kimberlites generally occur as diatremes and dikes and infrequently as sills. An extruded variety termed meimechite has been described from Russia. The diatremes are generally round to irregular in plan and pipe like (narrowing at depth) in three dimensions (Dawson, 1967).

There also appears to be a genetic relationship between kimberlites and carbonatites. Dawson (1964) stated that a complete gradation from kimberlite to alnoite to carbonatite exists. Strontium isotopic studies (Brookins, 1967a) indicate primary carbonatitic calcite in at least three of the Riley County kimberlites. The low Sr^{37}/Sr^{86} ratios of 0.7038 for the "pre-emplacement veins"

in the Pala kimberlite and 0.7048 for vein carbonate from Leonardville (this work) are very close to the average of 0.7032 for 32 carbonatites reported by Powell (1966).

Kimberlites are apparently related to deep seated tectonic activity and are generally within the stable continental platforms. Exceptions are the kimberlites of Malaita and Borneo which lie within orogenic belts.

Table 1 shows a chemical comparison of kimberlites with other igneous rocks.

Table 1. Comparison (wt. percent) of Kimberlites With Other Igneous Rocks

	Riley Co. Kimberlites	Ultrabasic	Basic	Intermediate	Syenite
SiO_2	22.61	40.6	51.3	55.6	62.2
TiO_2	1.31	0.05	1.5	1.3	0.58
Al_2O_3	3.63	0.85	16.5	16.7	16.6
FeO	9.35	12.6	10.9	7.5	4.7
MnO	0.19	0.19	0.26	0.15	0.12
MgO	22.58	42.9	7.4	3.6	0.96
CaO	16.06	1.0	9.4	6.5	2.5
K_2O	0.16	0.04	0.99	2.8	5.4
Na_2O	0.24	0.77	2.6	4.1	5.4
H_2O (−)	9.43	−	−	−	−
CO_2	10.96	0.04	0.04	0.07	−
P_2O_5	1.19	0.04	0.32	0.36	1.8
Total	101.24	99.08	101.21	98.68	100.26
Mg/Fe	2.43	3.4	0.5	0.4	0.15
K/Na	0.60	0.05	0.45	0.76	1.1

All data except Riley Co. Kimberlites from Dawson (1967)
Riley Co. Kimberlites from Brookins (in press)

ANALYTICAL PROCEDURES AND RESULTS

Sampling

The outcrop is texturally and mineralogically homogeneous at the surface. The rock which appeared to be obviously weathered was removed and fresh looking samples were taken from 12 to 36 inches beneath the surface. A total of about five hundred pounds of material was taken. Of that approximately one hundred pounds was crushed and sieved. The crushed rock which passed the 120 mesh (149 micron) sieve and was retained on the 200 mesh (74 micron) sieve was the fraction which was used for mineral recovery. Approximately ten pounds of sample was obtained. The fractions which were larger were unsuitable for mineral separation because of the large amount of rock fragments. The material smaller than 74 microns did not lend itself well to heavy liquid separation techniques.

Sample Separation and Purification

The ten pound sample was washed with distilled water to remove rock dust and air dried. Magnetite was removed by use of a hand magnet, and was further concentrated by successive washings and magnet treatments until essentually pure magnetite was obtained.

The non-magnetic material was separated into two fractions by the use of bromoform. The density of the bromoform (2.85) was continually checked with density cubes.

The light fraction (density < 2.85) was washed with ethanol to remove the bromoform, dried and separated into two aliquots. One aliquot was used without further treatment for x-ray analysis. The other fraction was soaked in cold 0.01 N HCl for 24 hours, filtered, dried, and the residue retained for x-ray analysis.

The fraction with density greater than 2.85 was similarly treated and separated into two fractions using a Frantz Isodynamic separator. The two fractions obtained were ilmenite-rich and a group of unidentified heavy minerals which could not be further separated by use of the Frantz separator. An attempt to separate this last fraction by the use of methylene iodide (D = 3.33) failed because the entire fraction sank. Magnetite, serpentine, ilmenite, heavy minerals and mica, which were hand picked, were prepared for analysis. In addition, about three grams of garnet which had been hand picked from the coarse, crushed fraction of the whole rock were prepared for analysis. The hand picked garnets were separated into purple and orange-yellow groups.

Refractive Index Measurements

The purple and orange-yellow fractions of the hand-picked garnets were prepared for refractive index measurement. They were hand-crushed in an agate mortar and pestle to a suitable size for measurement. Standard procedures using a polarizing microscope with white light and heavy index oils were applied. When a match or near match of the refractive index of the mineral with the refractive index of the oil was obtained the refractive index of the oil was immediately measured with an Abbe refractometer. The room temperature remained constant except for the oil on the slide which was under the microscope. Bloss (1961) suggests that for every degree centigrade increase the oil decreases about 0.0007 index units. Assuming the time any one slide spent on the microscope stage was equal to or less than the time necessary to raise the temperature of the index oil a maximum of $5^{o}C$, then the change in the index medium due to temperature change may be neglected because all determinations were rounded off to the third decimal place. This was done because the index of refraction axes of the correlation charts used for the determination of the molar percent of

the various garnet end numbers are published to only two decimal places
(Deer, Howie and Zussman, 1965; Sriramdas, 1957).

X-ray Diffraction

X-ray diffraction analysis was accomplished with the use of a Norelco
X-Ray Diffraction Unit, Ni - filtered Cu K α radiation with a diverging slit
of one degree, a receiving slit of 0.006 inches and an anti-scatter of one
degree. The scan speed was one degree per minute and the chart speed was one-
half inch per minute. The generator ran at 35 kilovolts and 13 milliamps. The
detector voltage was 1.7 kilovolts.

X-ray diffraction patterns were run on the following materials; magnetite,
serpentine, garnet, ilmenite, mica and the heavy mineral suite.

The samples were hand crushed in an agate mortar and pestle and passed
through a 74 micron sieve. All samples with the exception of the mica were run
as random powder mounts. The mica flakes which had been hand picked from the
whole rock were oriented with their cleavage planes parallel to the surface of
the glass slide. Most samples were run from 80° to 0° 2θ. All were run in
duplicate, some in triplicate. The ASTM Inorganic Card File was used exclus-
ively for identification and the results are tabulated in Tables 2 , 3 and 4 .
The minerals of the heavy fraction are barite, pyrite, apatite, zircon and
possibly chromite. The presence of zircon is suggested by its orange fluores-
cence under ultraviolet light. X-ray fluorescence established the total Sr of
the whole rock to be between 1000 and 1500 ppm. Lack of a proper standard
limited the determination to an estimate. The indexing procedures used were
those set forth by Klug and Alexander (1954) and the data are tabulated in
Appendix I.

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EXPLANATION OF TABLE 2

Physical properties and composition of garnets.

TABLE 2

Sample	a_o	n_o	Composition	Reference
Purple garnet	11.53 Å	1.755	$Py_{45}Al_{32}Gr_{23}$	1
Orange-yellow	11.56 Å	1.750	$Py_{53}Al_{28}Gr_{19}$	1
Red pyrope	11.5347 Å	1.747	$Py_{75}Al\text{-}An_{25}$	2
Green pyrope	11.5535 Å	1.753	$Py_{73}Al\text{-}An_{27}$	2
Kimberlite pyrope	11.535 Å	1.751	$Py_{55}Al_{30}Gr_{15}$	3
Kimberlite pyrope	11.535 Å	1.750	$Py_{55}Al_{30}Gr_{15}$	3
Kimberlite pyrope	11.537 Å	1.756	$Py_{51}Al_{32}Gr_{17}$	3

1. This work

2. Rosa (1966)

3. Nixon et al (1963)

Py - Pyrope - $Mg_3Al_2Si_3O_{12}$ Al - Almandine - $Fe_3Al_2Si_3O_{12}$

Gr - Grossularite - $Ca_3Al_2Si_2O_{12}$ An - Andradite - $Ca_3(Fe,Ti)_2Si_3O_{12}$

EXPLANATION OF TABLE 3

Physical properties of magnetite and ilmenite.

TABLE 3

Sample	a_o	c_o	Density	Reference
Magnetite	8.40 Å	–	5.18	1
Magnetite	8.3739 Å	–	–	2
Magnetite	8.3780 Å	–	–	3
Magnetite	8.3789 Å	–	–	4
Magnetite	8.396 Å	–	5.20	5
Ilmenite	5.06 Å	14.0 Å	4.39	1
Ilmenite	5.050 Å	14.14 Å	–	2
Ilmenite	5.0475 Å	14.140 Å	–	3
Ilmenite	5.089 Å	14.163 Å	4.74	5

1. This work

2. Rosa (1966)

3. Mc Dermott, Randolph #1, (M.S. Thesis in progress)

4. Mc Dermott, Randolph #2, (M. S. Thesis in progress)

5. Deer, Howie and Zussman (1966)

EXPLANATION OF TABLE 4

Sheet silicates with their C_o dimension.

TABLE 4

Sample	c_o	Reference
Lizardite	7.36 Å	1
Lizardite	7.36 Å	2
Antigorite	7.30 Å	2
Mica	14.4 Å	1
Chlorite	7.16 Å	2
Vermiculite	14.2 Å	2
Phlogopite	10.1 Å	2

1. This work

2. ASTM Inorganic Card File

Neutron Activation Analysis

Neutron activation analysis (NAA) of a whole rock sample was accomplished by utilizing the facilities of the Department of Nuclear Engineering of Kansas State University. The University has a TRIGA Mark II Reactor plus all necessary supporting facilities. Reactor time and counting equipment were graciously made available to the author for this phase of the investigation. The details of the Kansas State University reactor and facilities plus the theory and development of the NAA are presented by Eckhoff, et al (1968). A much more detailed treatment of general procedures is given by Lyon (1964).

To facilitate element identification in the whole rock sample, a standard was made with selected elements of known concentration (see Appendix II for elements and concentration). The whole rock sample was weighed, and placed in a clean polyethylene vial. The standard and the whole rock sample was then placed in the rotary specimen rack of the reactor, irradiated, removed and were counted separately in a lead shielded counting cavity. The spectrometer system used was a Nuclear Diode model #LGC - 3.8 - 4.4, 25 cubic centimeter Germanium, Lithium drifted crystal. The signal was then fed into a TMC Model 4096 Multi-parameter System for analysis. This system collects, stores, displays and prints out (plot, paper tape, magnetic tape) the gamma-ray interactions with the Ge (Li) scintillation crystal. Reference spectra were run so that spectrometer channel energies could be determined.

Determination of 774 ppm La, 19 ppm Sc and 13 ppm Sm was accomplished by direct comparison of the whole rock spectra with the spectra of the standard (see Appendix II for calculation technique). The presence of Tb, La, Lh, Tb, Eu, Fe, Cr, V, K and Co were also noted. Gamma ray energies and the identification of the various isotopes, which were determined, were checked against the results of other investigators (Gordon, et al, 1968; Stueber and Goles, 1967;

Haskin, et al, 1966).

Strontium Isotopic Composition

A fresh whole rock sample was crushed, ground and passed through a 200 mesh sieve. Three separate aliquots were prepared. Each was weighed and then soaked in vycor distilled 0.1 N cold HCl for eight hours. The aliquots were then filtered, dried and weighed again. A rough estimate of the total carbonate content of the rock was then made. The filtrate was collected and concentrated by evaporation. Standard procedures were used to avoid contamination and, except where noted, polypropylene laboratory ware was used. The strontium was separated from the concentrate by standard ion exchange techniques using Vycor distilled 2N HCl as eluant. The position of strontium on the column was monitored by use of Sr^{85} tracer. The strontium collected was evaporated to dryness on a hot plate in a Teflon beaker and the residue redissolved in about two milliliters of vycor distilled 2 N HCl. The concentrate was transferred to a 3 milliliter vycor microbeaker for storage. The same strontium extraction procedures were used on a composite garnet sample taken from the crushed whole rock and a calcite sample taken from a 3 centimeter thick vein. The Sr^{87}/Sr^{86} ratio for the whole rock is 0.709, the Sr^{87}/Sr^{86} of the garnet 0.706; and 0.7043 for the vein calcite. All the ratios were determined on the Geology Department's mass spectrometer by Dr. D. G. Brookins.

PETROGRAPHY

Hand Specimen Description

The Leonardville kimberlite is a green to bluish-green porphyritic rock
(Fig. 3). The phenocrysts, or insets of kimberlites, are referred to in the
literature as inclusions, xenoliths, xenocrysts or phenocrysts. The terminology
is not well established because of the genetic implications of the terms. For
this work, two terms will be used for all insets. Incorporated foreign material,
such as bits of country rock, will be termed inclusions. The term mineral grain,
with proper adjectives and modifiers, will be used to discuss all other remaining
material set in the groundmass.

Most inclusions are readily recognizable as angular fragments of shale that
are generally light green and range in size from a few microns to several centi-
meters. Two large (5-10 cm), rounded inclusions of what appear to have been
igneous rock have been found. The original rock types can only be guessed at
as the inclusions are severely altered (serpentinized). Both inclusions are
very similar to some inclusions at Stockdale (Brookins, 1969) which he called
igneous. The remainder of the inclusions are unidentifiable parentage but are
assumed to be shale and carbonate country rock.

The dominant mineral grains are light yellow-green, euhedral to anhedral
serpentine pseudomorphs of olivine and pyroxene. They range in diameter from
a fraction of a millimeter to five millimeters and most contain brown and black
patches which the author regards as incompletely serpentinized olivine or pyrox-
ene and magnetite, repectively.

Mica, garnet, ilmenite and magnetite form the remainder of the mineral grains.
The mica grains are elongate to circular, are well-rounded, range in diameter
from one to ten millimeters, and appear to have definite orientation. The

EXPLANATION OF FIGURE 3

Polished slab of the Leonardville kimberlite.

Figure 3

garnets are orange to purple, rounded, typically fractured, with or without kelyphite rimsand range from one to five millimeters. Ilmenite grains are rounded and also range from one to five millimeters. Magnetite has two modes of occurrence: in the kimberlite proper it occurs as irregular patches and blebs and may have some hematite associated with it. Discrete octahedra of magnetite are within calcite-filled veins in the rock.

The inclusions and mineral grains are set in a blue-gray aphanitic matrix (groundmass).

The polished slab (Fig. 3) clearly shows flow structure; the majority of the elongate inclusions and mineral grains have their long axes trending approximately in the same direction.

Based on hand specimen study, the Leonardville kimberlite is classified as a medium-grained intrusive kimberlite breccia with the minimum percentage of inclusions for that group (Dawson, 1967).

Thin Section Description

Twelve thin sections were studied. A modal analysis was not attempted because of the virtually complete serpentinization of the rock (see B, Fig. 4, for a typical view).

Inclusions

The inclusions of country rock are typically light-green to light-brown and are highly serpentinized. They are very fine-grained and many contain calcite filled veins. Much serpentine is so very fine grained that it appears isotropic and is called serpophite (Heinrich, 1965).

The mineralogy of the country rock inclusions is obscured by the very fine-grained texture and degree of serpentinization. Aside from serpophite and a few patches of calcite the only other minerals identifiable are 5-50 micron

EXPLANATION OF FIGURE 4

Photomicrographs from the Leonardville kimberlite.

(A) Serpentinized olivine grain, x 15. (B) General view,
x 15. (C) Garnet grain with kelyphite rim, x 15. (D) Mica
grain with exsolved opaques, x 15. (E) General view showing
bent mica grain, x 70. (F) Mica grain with kink bands, x 70.

Figure 4
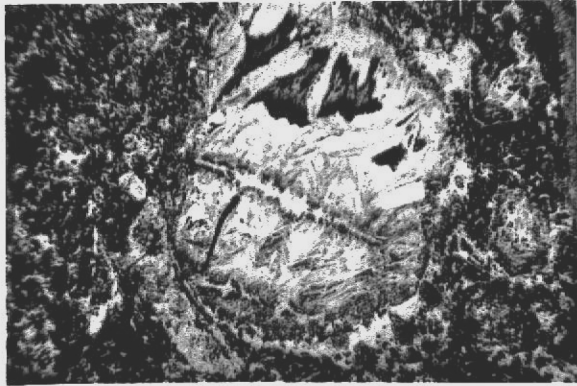
A

B

C

D

E

F

opaque cubes and rhombohedra, possibly magnetite and reddish-brown translucent patches, possibly hematite, (or goethite, or limonite).

Many inclusions of country rock have a "bleached" or lighter colored outer zone that grades into a darker interior. The lighter colored outer zone ranges from a fraction of a millimeter to as much as one to two millimeters, depending upon the overall size of the inclusion. The inclusion boundaries are very distinct and show little or no effect of abrasion.
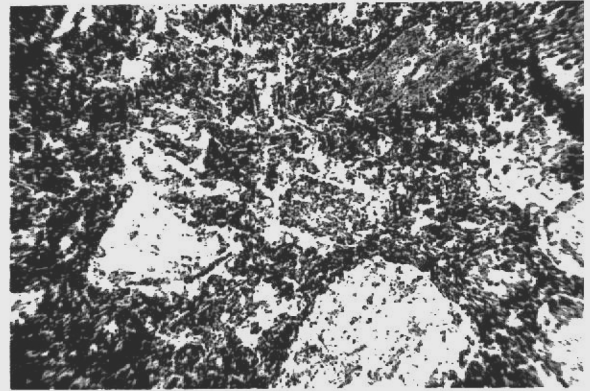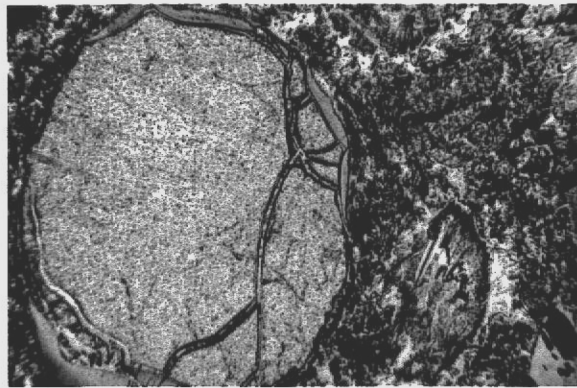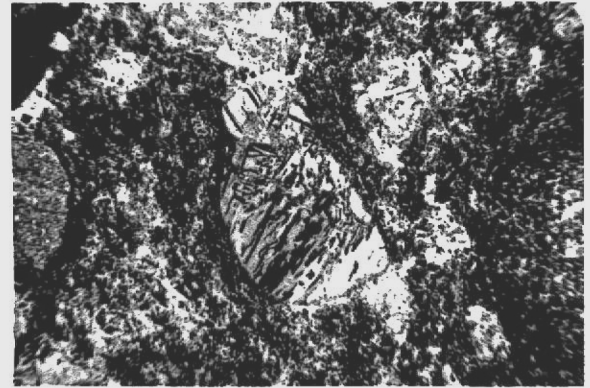
Two thin sections (LV - 2, LV - 6) contain inclusions thought to be igneous "basement" rocks; both inclusions are severely altered. The inclusion in LV - 2 contains strongly pleochroic biotite (optically negative, 2V about 5°) set in a mass composed largely of serpophite. Some of the material is incompletely altered and relict structures can be observed which are believed to be due to plagioclase twinning. If so, it is possible that the inclusion may have been a diorite. The inclusion in LV - 6 is larger and even more strongly altered; it consists of about 50 percent reddish-brown material, perhaps an alteration product of pyroxene and/or amphibole. The remainder of the inclusion is largely serpophite and incompletely altered material which may be feldspar. Thus the original rock may have been a gabbro. Both inclusions contain a number of veinlets filled with calcite and/or serpentine minerals. The boundaries of both inclusions are well defined and rounded.

Mineral Grains

The most abundant mineral grains are serpentine pseudomorphs of olivine and/or pyroxene that range from one half to five millimeters (see A and B, Fig. 4). In the twelve thin sections studied, serpentinization is so complete that positive identification of the original mineral is impossible. Olivine and pyroxene are assumed to have been the original minerals; this assumption is based on the shape of the grains, the alteration products and mode of occurrence. About 10

to 20 percent of these grains are euhedral with a shape typical of olivine and/ or pyroxene; the remainder are subhedral to anhedral. The subhedral to anhedral mode of occurrence of mineral grains is interpreted by many investigators as owing to rounding of the original crystals during the ascent of the kimberlite (Bckermann, 1967; Dawson, 1962).

The serpentine occurs as serpophite and in a fibrous, chevron or "hour-glass" motif (Deer, Howie and Zussman, 1965). Magnetite occurs as octahedra of 5 to 50 microns as well as irregular patches. Less commonly, the magnetite is distributed within a grain in such a way as to suggest that it formed along a fracture or cleavage plane. A rather common feature is irregular patches of a reddish-brown material, possibly hematite and/or incompletely altered original material.

In less severely altered kimberlites, in which the olivine and pyroxene can be identified, they fall near the general composition Fo_{90} and En_{93} respectively (Dawson, 1967).

The mica grains are well-rounded, many contain exsolved magnetite (D, Fig. 4) and range in diameter from a fraction of a millimeter to five millimeters. A few small mica grains have been observed which are not rounded (E, Fig. 4). Several grains contain one or more sets of kink bands (F, Fig. 4). The micas are generally moderate to strongly pleochroic, exhibit undulose extinction, have small 2V's ($0^\circ - 5^\circ$) and both positive and negative optic signs. The micas appear to be altered biotite or phlogopite.

The garnets range from fractions of a millimeter to as much as five milli-meters and are typically rounded and enclosed by a kelyphitic rim (C, Fig. 4). The fractures within the garnets are filled with serpentine minerals or carbon-ates or both. The kelyphitic rims are light green to light brown in color and are slightly to moderately pleochroic.

their shape and the fact that a whole rock chemical analysis yields 0.62 percent P_2O_5 (Table 6), the author believes these grains may be apatite.

DISCUSSION

Comparison of the Leonardville Kimberlite
With Other Riley County Kimberlites

General Geology

The geologic setting of the Riley County kimberlites has been noted earlier. The Winkler kimberlite is omitted from the ensuing discussion because only preliminary data have been reported (Brookins, 1970). Of the five remaining kimberlites, the Stockdale kimberlite is the only one which occurs as a topographic low at the bottom of a small stream, suggesting that it may have been emplaced along a fault or a large joint system. The other four kimberlites occur as slight to moderate topographic highs. Taylor (1950) suggests that Stockdale, Leonardville and Bala are high points on an East-West trending dike.

The contacts of Leonardville and Bala are not exposed but those at Stockdale and the two Randolph Pipes have been observed. At Stockdale, Rosa (1966) found a two to three inch indurated zone in the limestone which is in contact with the kimberlite. McDermott (M. S. Thesis in progress) found a similar zone of induration at the two Randolph sites. He also found the adjacent limestones at Randolph #1 to be dipping away from the kimberlite with 20-40° dips. The auger holes and trench at Randolph #2 indicate little or no disturbance of the country rock. Thus it appears that little or no pyrometamorphic effects have been incurred by the country rocks during kimberlite emplacement. The upturning of the country rocks at Randolph #1 suggests that at least the final emplacement event occurred under moderate pressures. Until Leonardville is trenched or cored it can only be assumed that these same features exist there as well.

The magnetic surveys by Cook (1955) and Dowell (1964) over the kimberlites

indicated that their structure at depth is remarkably similar. All appear to be pipe-like structures, narrowing at depth, vertical or steeply dipping to the south-east. The magnetic data indicated that the Leonardville kimberlite is the largest at near surface depths (Cook, 1955). Cook's magnetic anomaly map (Fig. 1) indicates that the near surface dimensions of the kimberlite are 1700 by 500 feet. The Leonardville magnetic map suggests that two separate parts of the kimberlite are very near the surface. Cook has interpreted his data to mean that the kimberlite was originally one intrusion which was subsequently off-set by a north trending fault. Cook's conclusion can only be verified by drilling as no evidence has been found in the vicinity suggesting faulting.

As noted earlier, an apparent relationship exists between the Riley County kimberlites and the Abiline Anticline, although at this point the exact relationship is not known. That the magnetic trends of the kimberlites (Fig. 2) are in each case approximately normal to the axis of the anticline indicates that the relationship is more than coincidental. It is reasonable to assume that during development of the anticline, concomitant regional flexure developed joint patterns which ultimately controlled the emplacement of the kimberlites.

The five outcropping kimberlites in Riley County are younger than Lower Permian rocks. Brookins (in press) concludes that the Riley County kimberlites are younger than the Lakota Group of the Cretaceous System, based upon a study of joint systems in Riley County and in the kimberlites themselves. Such an age is consistent with ages reported by Zartman et al (1967) for the Rose Dome and Hills' Pond ultramafic intrusions in Woodson County, Kansas, as well as other ultramafic intrusives in the central United States. However, it must be pointed out that the Woodson County locations are not kimberlite occurrences, rather, they are peridotites. Further, the emplacement of the intrusions

occurred at elevated temperatures as indicated by pyrometamorphism of the country rocks (Brookins, in press). With the present data, a reliable emplacement age cannot be definitely assigned to the Riley County kimberlites. The late-Cretaceous age suggested by Brookins (in press) shall be adopted for the Leonardville kimberlite.

Petrography

The five Riley County kimberlites are dark to light green in their overall appearance, with varying amounts of inclusions and mineral grains (Fig. 3 and A-D, Fig. 5). Leonardville (Fig. 3) and Stockdale (C, Fig. 5) contain the most inclusions and mineral grains which given them a distinctly porphyritic, brecciated appearance. Dozens of igneous and metamorphic inclusions, ranging up to 15 centimeters in diameter, have been recovered from Stockdale. These inclusions from Stockdale include gneiss, diorite, pyroxenite, gabbro, granulite, and eclogite (Brookins, 1969a). The two igneous inclusions at Leonardville are indistinguishable from similar inclusions at Stockdale. The country rock inclusions in Stockdale and Leonardville are similar in size and abundance. The major difference is the degree of alteration. Stockdale, which outcrops at the bottom of an intermittent stream valley, is subjected to considerably more water-promoted types of weathering than is Leonardville.

The Bala and Randolph #1 kimberlites (D, A, Fig. 5) have fewer inclusions, which gives them somewhat less of a brecciated appearance. Both are reported to contain igneous, metamorphic and country rock inclusions, but at a much lower level of abundance (Brookins, 1969a). The author has collected fist-sized pieces of crystalline carbonate rock from Bala but has not observed similar inclusions at the other four kimberlite sites.
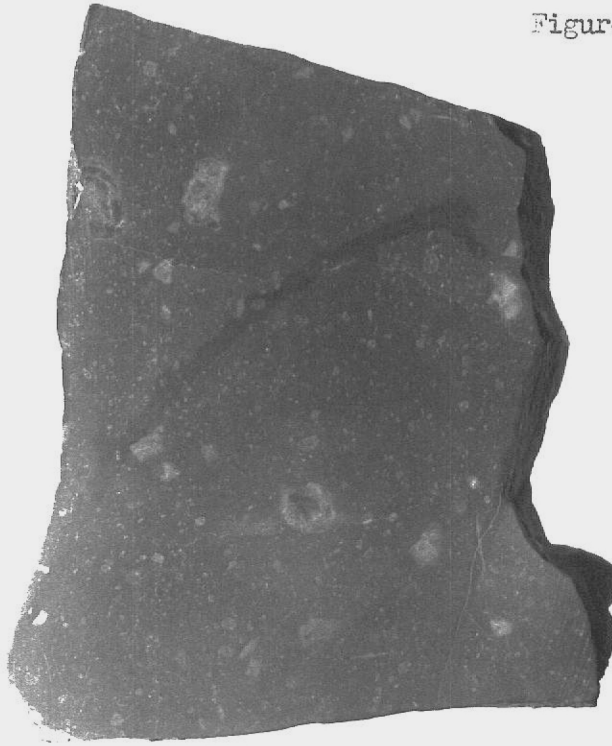
Randolph #2 (B, Fig. 5) is the lightest in color of the Riley County

EXPLANATION OF FIGURE 5

Polished slabs of other Riley County kimberlites.
(A) Randolph #1 kimberlite. (B) Randolph #2 kimber-
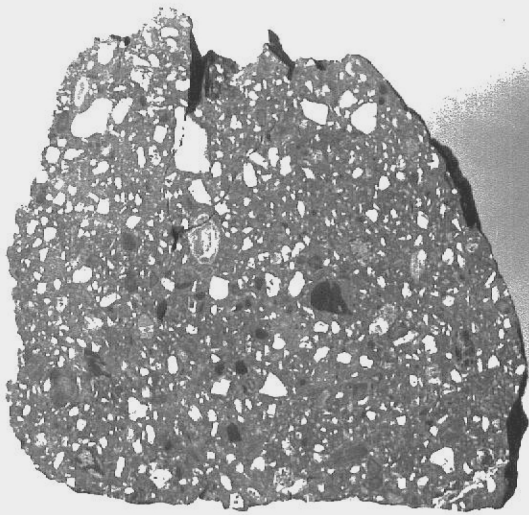lite. (C) Stockdale kimberlite. (D) Bala kimberlite.

Figure 5
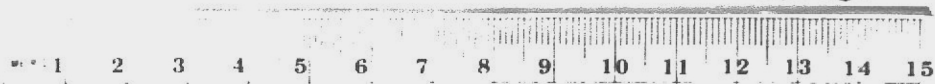
kimberlites and contains the fewest number of inclusions. McDermott (M. S. Thesis in progress) states that Randolph #2 contains "inclusions and xenoliths" (pg. 23) but does not describe them.

The mineral grains in Stockdale are very similar in type, morphology and abundance to those found in Leonardville, but different in size. The garnet, mica, ilmenite and magnetite are typically larger at Stockdale. Further, the alteration of the olivine and/or pyroxene is much more extensive in Stockdale; probably due to the greater volume of water affecting it.

The only readily identifiable mineral grains in the Bala and two Randolph kimberlites are the altered olivines and/or pyroxenes. Garnet and mica have not been found in the Randolph #2 kimberlite and are rare in Bala and Randolph #1. The opaques in the Bala and two Randolph kimberlites are very fine-grained and are difficult to see with the unaided eye. The Bala kimberlite is the exception: In addition to the fine grained opaques, veins of opaque material up to 2 millimeters in width can be observed.

Thin section study of the five Riley County kimberlites (see Table 5 for modal analysis of four kimberlites) yields one common feature: pervasive serpentinization. The serpentine minerals occur in the matrix of the kimberlites, in included country and basement rocks, and as alteration products of olivine and pyroxene. Many serpentine pseudomorphs occur as euhedral mineral grains but others partially or completely lack crystal outlines. The two Randolph intrusions contain the greatest number of euhedral pseudomorphs after olivine and/or pyroxene, followed, in decreasing abundance, by Bala, Stockdale and Leonardville.

Carbonate replacement, complete or partial, of the olivine and pyroxene pseudomorphs is also common in the kimberlites. The most extensive carbonate replacement of the pseudomorphs occurs at the two Randolph intrusions; and

EXPLANATION OF TABLE 5

Modal analysis (volume percent) of Riley County kim-
berlites. S - Rosa (1966). R-1 and R-2 - McDermott
(M. S. Thesis in progress). B - Eastwood (1965).

TABLE 5

	S	R-1	R-2	B
Antigorite	39.2	38.2	42.0	58.0
Pyroxene	7.6	16.0	11.3	–
Olivene	3.5	7.4	7.5	–
Perovskite	4.5	T	T	–
Magnetite	6.4	7.9	6.2	14.0
Ilmenite	3.3	2.2	3.0	1.0
Chlorite	5.4	1.0	1.3	7.0
Phlogopite	0.8	1.2	T	T
Green Pyrope	1.6	–	–	–
Red Pyrope	2.2	–	T	–
Chrysotile	0.6	T	T	T
Carbonates	19.7	21.1	26.2	17.0
Apatite	–	1.8	1.0	–
Leucoxene	T	T	T	T
Biotite	0.1	–	–	T
Chromite	T	T	T	T
Rutile	T	T	T	–
Quartz	T	T	T	–
Chalcedony	T	–	–	–
Silica	T	–	–	–
Hem-Lim	T	T	T	T
Rx Fragments	–	2.6	1.0	–
Zircon	–	–	–	T
Totals	94.9	99.4	99.5	97.0

(again) in decreasing amounts at Bala, Stockdale and is rarest at Leonardville. Carbonate is ubiquitous in the matrix of the Riley County kimberlites, although the amount varies from site to site. Veins of carbonate material, ranging from fractions of a millimeter to several centimeters, are at all of the kimberlite sites.

The garnet grains at Stockdale are similar to those at Leonardville, but are slightly larger, with or without kelyphite rims and slightly more abundant. A green pyrope, which is rare, has been described from Stockdale (Rosa, 1966) but has not been found at Leonardville. Garnets of any kind are very rare at Randolph #1 and Bala and are extremely rare at Randolph #2.

Mica is nearly as abundant at Stockdale as at Leonardville. Aside from the Leonardville kimberlite, Stockdale is the only other location where kink banding has been observed in the micas. As at Leonardville, the Stockdale mica occurs with any or all of the following; one or more sets of kink bands, low 2V, positive or negative optic sign, undulose extinction, and exsolved opaques. At Randolph #1 and Bala, mica occurs in very small fragments in the groundmass and only at trace levels. Mica has yet to be observed at Randolph #2.

Opaque minerals are abundant in all Riley County kimberlites. Magnetite is in all phases of the kimberlites (inclusions, mineral grains, matrix, small veins) whereas ilmenite occurs as discrete grains up to a centimeter in maximum dimension in the matrix. The larger opaque mineral grains are in Leonardville and Stockdale whereas Bala and the two Randolph kimberlites contain the finer-grained opaques.

Brookins (1970) has compiled a list of over fifty minerals occurring in the Riley County kimberlites. The overwhelming majority of these minerals can be identified only by optical, x-ray and chemical methods. Notable among these

are: apatite, barite, chromite, leucoxene, perovskite, phlogopite and rutile.

Geochemistry

Major element analyses are available for all Riley County kimberlites
except Stockdale (Table 6). Four kimberlites are chemically equivalent: All
element percentages and element ratios are within the same order of magnitude
and suggest similar parent material and emplacement histories for the four
kimberlites. Minor chemical variations are probably insignificant, although
Eastwood (1964) stated that Bala and Stockdale are differentiated with respect
to each other. The minor chemical variations probably reflect the mineralogical
differences which do exist between the different kimberlites.

One of the two major constituents of the Riley County kimberlites is
serpentine. Many investigators of the Riley County kimberlites disagree about
the composition of the serpentine polymorphs. Eastwood (1964) reported anti-
gorite and traces of chryotite in Bala. Rosa (1966, p. 21) reported that
"antigorite and the other serpentine minerals are recognized in thin section ...".
McDermott (M. S. Thesis in progress) also optically identified antigorite and
traces of chrysotile. This investigation found the Leonardville serpentine,
based upon x-ray diffraction studies, to be composed mostly of lizardite and
small amounts of antigorite.

Serpentine minerals in the Riley County kimberlites occur in the matrix,
altered mineral grains and in inclusions. A question which must be asked is,
was all the serpentine formed during a single event? Regarding this question,
McDermott (M. S. Thesis in progress) in his study of the two Randolph kimber-
lites, believes that serpentinization occurred prior to final emplacement.
After his study of Bala and Stockdale, Eastwood (1965, p. 34) concluded that
"Serpentinization occurred during injection ...". Rosa (1966, p. 51) stated

EXPLANATION OF TABLE 6

Chemical analysis (wt. percent) of Riley County kimberlites. L - Leonardville, R-1 - Randolph #1, R-2 - Randolph #2, B - Bala. Data from Brookins (in press).

TABLE 6

	L	R-1	R-2	B
SiO_2	24.15	22.91	21.13	22.23
TiO_2	1.50	1.72	1.80	2.20
Al_2O_3	2.03	4.63	4.28	3.59
Cr_2O_3	-	0.12	0.12	0.18
Fe_2O_3	6.51	6.80	7.44	7.19
FeO	1.85	2.94	1.79	2.89
CaO	15.87	16.68	18.62	13.07
MgO	24.45	20.36	20.04	25.47
Na_2O	0.15	0.51	0.27	0.04
K_2O	0.15	0.15	0.16	0.02
H_2O (+)	8.50	8.76	8.65	9.81
H_2O (−)	0.84	1.79	1.31	1.71
CO_2	12.04	10.69	11.72	9.33
MnO	-	0.14	0.22	0.21
P_2O_5	0.62	1.19	1.39	1.56
SO_3	0.20	0.29	0.34	0.24
Total	98.86	99.68	99.28	99.79
Fe^{+3}/Fe^{+2}	3.52	2.73	4.16	2.49
Mg/Fe	2.93	2.09	2.17	2.53
K/Na	1.00	0.29	0.59	0.50

"Serpentinization [of Stockdale] occurred before emplacement". Clearly, these investigators have not addressed themselves to the question regarding the three modes of occurrence of the serpentine minerals. Apparently they assumed that serpentinization occurred during a single event. If so, then Rosa was in error because his conclusion does not account for serpentinization of the shale country rocks which must have been incorporated into the kimberlite during emplacement. Thus Eastwood's conclusion is partially substantiated. Still an attempt must be made to resolve the question of contemporaneity of the serpentine pseudomorphs and the serpentine of the matrix.

Bowen and Tuttle (1949) stated that serpentinization of forsterite by water cannot occur above 400°C. Turner's (1968) suggested equation of olivine, enstatite and water reacting to form serpentine minerals and magnetite, is consistent with the petrologic data and will be adopted for this work. The author assumes that serpentinization of olivine and/or pyroxene in the kimberlites did not begin until the system was well within the earth's crust as is shown by the position of the 400°C isotherm (B, Fig. 6).

The serpentine minerals of the matrix offer no morphological clue as to what the original material may have been. Wherever their origin may be, the author believes that the matrix serpentine pre-dates the serpentinization of the olivine or pyroxene because the pseudomorph grain boundaries are so distinct. Had serpentinization of the olivine or pyroxene been simultaneous with the serpentinization of the matrix then grain boundaries would be less distinct and blurred, grading into and becoming the same as the irregular patches and blebs of the matrix serpentine, but that has not been observed.

Meteoric waters may have influenced the serpentinization of kimberlites slightly. Brookins (in press) notes that the 150 feet of cores from Bala have suffered the same degree of apparent alteration as the material which crops out.

EXPLANATION OF FIGURE 6

(A) Pressure, depth - temperature plot for graphite - diamond and enstatite plus spinel going to pyrope and forsterite (modified from Boyd and MacGregor, 1964).

(B) Possible mantle - crust configuration. (after Boyd and MacGregor, 1964).

Figure 6

Temperature, °C

1600
1400
1200
1000
800
600
400
200

En+Sp=Py+Fo

A
B

G=D

En – Enstatite
Py – Pyrope
Sp – Spinel
Fo – Forsterite
G – Graphite
D – Diamond
A – Oceanic
   geotherm
B – Continental
   geotherm

A

100   200   300
Depth, kilometers

10 20 30 40 50 60 70 80 90 100
Pressure, kilobars

B

Precambrian Shield	Continental Margin	Cont. Shelf	Oceanic area

Depth, kilometers

Continental Crust

Oceanic Crust

20 — 200°C —
   — 400°C —
40
   — 600°C —
60
   — 800°C —
80
100

Forsterite + Al-poor Pyroxene + Spinel

Forsterite + Al-rich Pyroxene

Forsterite + Al-poor Pyroxene + Garnet

— 1000°C —

Carbonate minerals, (mostly calcite) are the second most abundant constit-
uents of the Riley County kimberlites. Traces of dolomite are in thin sections
from Leonardville, but is too rare to show in the x-ray diffractograms. Leaching
of finely ground, fresh whole rock samples indicates that the total carbonate
mineral content of Leonardville is about 20-25 percent by weight.

Brookins (1967a) studied the strontium in the carbonate material of both
of the Randolph and Bala kimberlites and found at least two generations of
calcite. The Sr^{87}/Sr^{86} ratio of the post-emplacement veins averages about
0.709 and the Sr content is about 300 ppm. The Sr^{87}/Sr^{86} ratio of the country
rocks is slightly lower, at 0.708 and contains about 340 ppm Sr. The pre-
emplacement veins, on the other hand, have Sr^{87}/Sr^{86} ratios averaging 0.7038
and a total average Sr content of 4280 ppm. These data indicate two sources
of carbonate material; one, apparently being the local county rocks, and the
other being primary (carbonatitic). The Sr date of pre-emplacement vein is
consistent with Powell's (1966) work on carbonatites. He found Sr^{87}/Sr^{86}
ratios values of carbonatites from 0.702 to 0.705 and that of most sedimentary
carbonates to be from 0.706 to 0.713. Runnels and Schleicher (1936) found the
total Sr of 277 Eastern Kansas limestones to average at 490 ppm. Gold (1963)
reported an average of 3500 ppm Sr for carbonatites.

The Sr^{87}/Sr^{86} ratio of 0.7090 for the Leonardville whole rock agrees with
Brookins average value of 0.7086 for the post-emplacement veins at both Randolph
sites and Bala. The two values fall on the mode of sedimentary values reported
by Powell (1966); Brookins (1967a) reported a Sr^{87}/Sr^{86} average ratio of 0.7081
for ten eastern Kansas limestones. Based on the foregoing evidence it appears
that most carbonate in the Leonardville kimberlite is local and not primary
(carbonatitic). However, the three centimeter thick carbonate vein at
Leonardville has a Sr^{87}/Sr^{86} ratio of 0.7043 which falls within the range Powell

(1966) reported for carbonatites. Thus the carbonate vein at Leonardville probably was not derived from local limestones and may be carbonatitic.

The estimated whole rock strontium value of 1000-1500 ppm suggests that two sources of carbonate exist; low total strontium limestone and high strontium carbonatite.

The magnetite from Leonardville more closely resembles the ideal magnetite molecule, $Fe^{+2}Fe^{+3}_2O_4$, than does the magnetite from the other Riley County kimberlites. Deer, Howie and Zussman (1966) listed unit cell of $8.396\text{\AA}$ and a density of 5.20 for ideal magnetite. This investigation found the magnetite from Leonardville to have a unit cell of $8.40\text{\AA}$ and a density of 5.18, which indicates that it is very close in composition to the ideal molecule. The magnetite from Stockdale has a unit cell of $8.3789\text{ \AA}$ (Rosa, 1966), and magnetite from Randolph No. 1 reportedly has a unit cell of $8.3780\text{ \AA}$ and that from Randolph No. 2, $8.3789\text{ \AA}$ (McDermott, M. S. Thesis in progress). But McDermott also reports a "typical sample" (Table 5, appendix) with a unit cell of 8.3934 $\text{\AA}$. Based upon the smaller unit cell determination McDermott concludes that the mineral is composed of 93.5 percent magnetite, 6.5 percent hercynite and some possible Cr. From this information McDermott suggests that magnetite is secondary, obtaining Al which was released during the serpentinization of the whole rock system.

McDermott's criterion for deducing that the magnetite is secondary cannot be used for the Leonardville magnetite because of its almost 100 percent ideal composition and because the author does not believe that serpentinization occurred as a single event. Because discrete magnetite crystals are in all three modes of serpentine occurrences, the author assumes that magnetite formed during at least two separate events.

Ilmenite from Leonardville has smaller unit cell dimensions than those of

the ideal molecule $FeTiO_3$: $a_o = 5.089$ Å and $C_o = 14.163$ Å (Deer, Howie and Zussman, 1966). The smaller dimensions of the ilmentite from the Leonardville kimberlite may be indicative of the hematite molecule, Fe_2O_3, which has $a_o = 5.0305$ Å and $C_o = 13.749$ Å (Deer, Howie and Zussman, 1966), or of the geikielite molecule, $MgTiO_3$, which has $a_o = 5.054$ Å and $C_o = 13.898$ Å (ASTM card #6-0494, inorganic materials). Either hematite and/or geikielite will decrease the unit cell of ilmenite. Brookins (in press) arrived at the same conclusion regarding ilmenite from Stockdale and the two Randolph kimberlites.

Leonardville and Stockdale contain an abundance of mica which was analyzed by x-ray diffraction. Rosa (1966) reported that the mica from Stockdale is mostly chlorite, some phlogopite and traces of vermiculite. X-ray diffraction analysis of the Leonardville mica failed to demonstrate existence of phlogopite, although it may have been phlogopite originally. The Leonardville mica consists of chlorite, and traces of vermiculite, which indicates complete alteration of the original mica.

A common feature of many mica grains is kink banding (F, Fig. 4). Kink banding is considered by Short (1966) to be a shock feature. Many investigators feel that an explosive event is an integral part of kimberlite emplacement, hence one can assume that the kink banding in the micas resulted from a similar event at some time during the emplacement history of the Leonardville kimberlite. Kink banding has also been described in micas from the Stockdale kimberlite (Brookins, in press). Raleigh (1967) presented evidence that kink banding in ultramafic rocks results from high temperatures exerted during conditions of deformation. This could also account for the kink bands in the micas occurring during emplacement of the kimberlite in a plastic state. Both types of conditions probably occurred during the history of the kimberlite system. Since conditions of high pressure deformation probably occurred throughout most of

the system's history nothing can be said about the time of kinking.

K-Ar dates on micas from Leonardville and Stockdale have been presented
by Rosa (1966) and Brookins (1969b): Rosa presented two ages 331 ± 50 m.y.
and 142 ± 20 m.y. on Stockdale micas and Brookins (in press) presents ages
of 315 ± 20 m.y. and 380 ± 40 m.y. for Stockdale micas, 204 ± 20 m.y. age on
mica from Leonardville and 95 ± 10 m.y. on a chloritized phlogopite from the
Winkler occurrence.

The spread of the ages, about 300 m.y., and the degree of chloritization
of the micas does not allow any inferences to be made regarding the time of
crystallization of the micas or kimberlites. But Brookins (1969b) has used
the K-Ar data to estimate a temperature of final emplacement of $75^{\circ}-150^{\circ}C$.

Garnets have been analyzed from only Leonardville and Stockdale. From
his data, Rosa (1966) concluded that the red garnet from Stockdale is 75 per-
cent pyrope and 25 percent almandine – andradite and that the green garnet is
73 percent pyrope and 27 percent almandine – andradite, making the Stockdale
garnets among the highest in pyrope content known. The Stockdale garnet anal-
yzed for its chromium content (Brookins, 1967c) corresponds to chromium contents
of garnets from Basutoland kimberlites (Nixon, et al, 1963). Brookins' corrected
analysis of 2.77 percent Cr_2O_3 (Bagrowski, 1941 had reported 7.90 percent Cr_2O_3)
is very similar to the analysis reported by Nixon. Further it is consistent
with Nixon's reported value of 1.747 for the index of refraction of the garnets
and indicates that no uvarovite is present. Rosa's (1966) plot of index of
refraction vs. unit cell for the Stockdale garnets lends further support to the
same conclusion. This investigation shows that the garnets from Leonardville
contain, on the average, 30 percent almandine, 20 percent grossularite, and 50
percent pyrope. The least amount of pyrope is 45 percent in the purple garnets
and the highest is 53 percent in the orange-yellow garnets. The variation in

color, composition and structural dimensions suggest that the garnets from both kimberlites did not crystallize at the same time but continuously during the early history of the system.

That the garnets in the Leonardville and Stockdale kimberlites are not euhedral but are rounded and fractured also suggests that they were formed before emplacement, undergoing rounding and fracturing during emplacement of the kimberlite.

Boyd and MacGregor (1963) and others indicate that garnet is a high pressure-high temperature mineral. Phase equilibra data (see A, Fig. 6) indicate that the minimum temperature of formation of pyrope-rich garnet is about $450^{\circ}C - 500^{\circ}C$ and 10 - 15 kilobars pressure. These conditions correspond to a depth of approximately 40 - 50 kilometers.

The Sr^{87}/Sr^{86} ratio of 0.7076 obtained from garnet from Leonardville, if real, indicates that the garnet was not derived from the mantle. Hurley (1967) presented evidence that present mantle Sr^{87}/Sr^{86} ratios should range from 0.702 to 0.704. If the Leonardville garnet is mantle derived then its Sr^{87}/Sr^{86} ratio has been altered. Brookins (in press) obtained a Sr^{87}/Sr^{86} ratio of 0.7186 for a pyrope from Stockdale and, assuming an initial Sr^{87}/Sr^{86} ratio of 0.702, he calculated an age of 745 ± 100 m.y. The age is well in excess of the proposed age of emplacement of the Riley County kimberlites and probably reflects trapped Rb^{87}, which occurred during the garnet crystallization or loss of daughter product Sr^{87} by thermal diffusion prior to emplacement.

Perovskite has been identified at Stockdale and the two Randolph kimberlites but not at Bala (Table 5). Its presence could not be definitely established at Leonardville, although the author believes it to be present as opaque to slightly translucent, one to ten micron cubes and rhombohedra in the kimberlite matrix.

Apatite has not been identified at Stockdale or Bala but has been at the

two Randolph locations (Table 5). The author believes it to be present at
Leonardville and the analyses in Table 5   suggest that it probably occurs at
Fala.

The barite identified in the heavy mineral fraction (Leonardville only)
is rather uncommon for ultramafic rocks, but not so for carbonatites. Heinrich
(1966) reported barite to be common and may even be essential in carbonatites.
Thus further support is gained for the carbonatitic source for some of the
carbonate in the Riley County kimberlites. The support is tenuous however, as
barite is a common vein or cavity filler in limestone, sandstone and shale
(Deer, Howie and Zussman, 1966). Barite has not been reported from the other
Riley County kimberlites.

In summary, all five Riley County kimberlites were emplaced approximately
at the same time, under similar conditions and were derived from a common
source. The minor variations in the whole rock chemistry and the different
textures and mineralogies probably reflect each kimberlite's unique emplacement
history after separation from the common parent. A genetic relationship may
exist between the Riley County kimberlites and carbonatites.

Comparison of Riley County Kimberlites
With Other Kimberlites in the World

Kimberlites are distributed throughout the world on all the major contin-
ents except Antarctica. No doubt, in time, they shall be discovered there as
well. In North America they are in Quebec and Ontario in Canada. In the
United States they occur, in addition to Kansas, in New York, Pennsylvania,
Virginia, Kentucky, Tennessee, Illinois, Missouri, Arkansas, Arizona, Utah
and New Mexico. Elsewhere they are in Brazil, Australia, the Salomon Islands,
Borneo, India, Russia, Czechoslovakia, Norway and Sweden. On the African con-
tinent they are in West Africa, Angola, the Congo, Tanzania, Rhodesia, South

Africa, South West Africa and Basutoland.

The Riley County kimberlites are considered to be typical when compared with kimberlites occurring elsewhere in the world. Although their size (volume) appears to be smaller than the average, their funnel shape, narrowing at depth (diatreme), is very typical. The manner of emplacement of the Riley County kimberlites is also similar to many kimberlites. They have been emplaced along zones of weakness. In Kansas the zones of weakness are well defined joint patterns which account for the definite orientation of the magnetic trends of the kimberlites. Elsewhere in the world the diatremes are typically associated with dikes, sometimes grading into them (Dawson, 1967). Kimberlite dikes have not been observed in Riley County. Another common, possibly essential, feature of kimberlites including those in Riley County is the absence of pyrometamorphic effects on the country rocks. The low temperature of emplacement is dramatically illustrated at several localities throughout the world. Notable are some of the African kimberlites described by Williams (1932) in his classic work on the genesis of diamonds. He noted that included logs, coal and oil bearing shales were essentially unaltered, which suggests a temperature of emplacement consistent with Brookins (in press) estimate of 75°-150°C for the Riley County kimberlites.

Table 7 lists major chemical element analyses for many kimberlites from various localities. With the possible exception of kimberlite tuff from Buell Park, Arizona, the remainder may be considered as chemically equivalent. Minor variations do exist but they probably reflect local differences in emplacement conditions and histories for each kimberlite or group of kimberlites. The concentrations of La and Sc determined from the Leonardville kimberlite are strikingly similar to those reported by Dawson (1967) for African and Russian kimberlites. The Leonardville kimberlite contains 774 ppm La, 19 ppm Sc and 13 ppm

EXPLANATION OF TABLE 7

Chemical comparison (wt. percent) of average Kansas kim-
berlite with average kimberlites from Canada, Russia and
Africa. Kansas kimberlites, Brookins (in press). Canadian
kimberlites, Watson (1967b). Russian kimberlites, Davidson
(1967a). African kimberlites, Dawson (1967a).

TABLE 7

	Man.	Can.	USSR	African
SiO_2	22.61	24.15	27.81	31.76
TiO_2	1.81	6.46	1.63	2.22
Al_2O_3	3.63	2.58	3.40	4.28
Fe_2O_3	6.90	7.67	5.40	7.62
FeO	2.37	8.36	2.85	3.91
MnO	0.19	0.16	0.12	0.17
MgO	22.58	24.03	25.53	27.47
CaO	16.06	10.27	12.21	8.11
K_2O	0.16	1.02	0.66	1.43
Na_2O	0.24	0.25	0.33	0.22
H_2O (+)	8.93	4.98	–	7.96
H_2O (–)	1.41	0.90	–	1.29
CO_2	10.96	9.02	–	3.90
P_2O_5	1.19	0.23	0.50	1.14
Total	99.04	100.08	80.44	101.48

Sm, whereas Dawson (1967) reported an average of 370 ppm La and 25 ppm Sc for 14 Basutoland kimberlites. Stueber, et al, (1967) reported an average of 14 ppm Sc for three African kimberlites and Haskin, et al, (1966) reported 8.0 ppm Sm for an average of three different African pipes. Several dozen Yakutia kimberlites are reported to contain 10 ppm Sc, and 1140 ppm Sr; the latter is comparable to the 1000-1500 ppm Sr estimate for Leonardville.

The petrography and mineralogy of the Riley County kimberlites have been described earlier. The Riley County kimberlites are almost identical to the typical kimberlite based on petrographic descriptions given by Dawson (1967). Similarities include the kimberlites' mineralogy, texture, matrix and the nature and variety of inclusions. The major difference between the Riley County kimberlites and some kimberlites in the world is that, to date, diamonds have not yet been found in the former. The second and third major differences are that Riley County kimberlites are extremely silica deficient, somewhat below the world average, and they are virtually completely serpentinized whereas others are only partially so.

A study of the ages of the kimberlites of the world reveals that most of them fall within specific time intervals (Dawson, 1967): 2100 to 2300, 1150, 700, and 80 to 100 m.y. ages are suggested based upon a study of kimberlite activity in West Africa. As noted earlier, the Riley County kimberlites appear to have been emplaced during the post upper lower Cretaceous (90-100 m.y.) Kennedy and Nordlie (1968) note that "A startling majority of kimberlite pipes, perhaps as much as 90 percent, were all emplaced in late Cretaceous time".

The logs and coal that Williams (1932) noted at the Kimberley, De Beers and Wesselton mines poses a very interesting question. How did these materials, which were presumably derived from the 1/2 mile stratigraphically higher Karoo Formation, get to such a low level? This fact is difficult to explain partic-

ularly since these materials have such a low specific gravity and the fact that the logs and coal are mingled with high specific gravity materials such as peridotite, garnet and diamond which have been brought up from great depth. Mikheyenko and Nenashev (1960), in an attempt to solve this problem, have proposed that kimberlites are emplaced as a cold solid behaving as a fluid under gravitational and tectonic pressures. During the emplacement, they believed that convection cells develop, thereby allowing material at higher elevations to be dragged down and, conversly, materials at lower elevation brought up.

The Riley County kimberlites are near the center of the continental United States and a few hundred miles south of the Canadian Shield. Their location is coincident with Dawson's (1967, pg. 251) statement "Most kimberlites are confined to the interior and margins of the shield on the stable platforms of continental areas".

In summary then; the Riley County kimberlites are indeed bonafide members of the well established group of rocks defined as kimberlites. Their chemistry, mineralogy, petrography, emplacement modes, age and tectonic setting are consistent with kimberlites elsewhere in the world.

CONCLUSIONS

The following statements, based on the foregoing data and discussion, are applicable.

The Leonardville kimberlite is probably the largest (volume) of the six known Riley County kimberlites and contains abundant inclusions of country rock shale. The rare igneous inclusions at Leonardville may be "basement" material. The Leonardville kimberlite is petrographically similar to the Stockdale kimberlite and is chemically equivalent to the Bala and Randolph kimberlites.

The Leonardville kimberlite is heavily serpentinized and carbonated: Lizardite is the predominant serpentine mineral and calcite is the most abundant carbonate mineral (about 25 weight percent of the whole rock). Much of the serpentine occurs as pseudomorphs after olivine and/or pyroxene. Both primary (carbonatitic) and secondary (sedimentary) sources of carbonate are present at Leonardville. Some of the mica grains have kink bands and all have been completely altered to chlorite and vermiculite. The magnetite is nearly 100 percent Fe_3O_4 and the garnets are composed of approximately 50 percent pyrope, 30 percent almandine and 20 percent grossularite.

The garnets formed continuously throughout the early history of the kimberlite at depths greater than 40-50 kilometers and were altered prior to or during final emplacement. Serpentinization and formation of magnetite occurred during at least two different events: the earliest being at about 30 kilometers depth and the latest during or close to final emplacement. The kimberlite was emplaced at a relatively low temperature (75° to 150° C) as a mush-like mass. The probable Late Cretaceous emplacement of the kimberlite was controlled by pre-existing joint patterns.

ACKNOWLEDGMENTS

I would like to thank Dr. D. G. Brookins for many hours of fruitful discussion and for his guidance, without which, this work could not have been accomplished. I would also like to express my gratitude to Dr. P. C. Twiss, Dr. R. W. Vian and Dr. A. C. Andrews for their many helpful suggestions.

The financial assistance supplied by an N.D.E.A. Fellowship was gratefully appreciated.

Finally, a heart-felt thanks to my wife for her encouragement and all the typing.

APPENDIX I

EXPLANATION OF TABLE I

X-ray data and a_o calculation for purple garnet.

TABLE I

hkl	Intensity	$d\overset{\circ}{A}$	$n=h^2+k^2+l^2$	$\sqrt{n}$	$a_o=\sqrt{n}\ d\overset{\circ}{A}$
400	10	2.91	16	4.00	11.64
420	100	2.59	20	4.47	11.58
332	21	2.47	22	4.69	11.58
422	32	2.37	24	4.90	11.61
510	24	2.27	26	5.10	11.58
521	29	2.11	30	5.48	11.56
440	3	2.05	32	5.66	11.60
611	5	1.88	38	6.16	11.58
620	4	1.83	40	6.32	11.57
640	6	1.60	52	7.21	11.54
642	25	1.55	56	7.48	11.59
800	4	1.45	64	8.00	11.60
840	52	1.29	80	8.94	11.53
842	27	1.26	84	9.17	11.55
664	7	1.23	88	9.38	11.54
930	4	1.22	90	9.48	11.57
941	3	1.17	98	9.90	11.58

Sum of a_o's = 196.80

Average a_o = 11.58 Å

EXPLANATION OF TABLE II

X-ray data and a_o calculation for orange – yellow garnet.

TABLE II

hkl	Intensity	$d\text{Å}$	$m=h^2+k^2+l^2$	$\sqrt{m}$	$a_o=\sqrt{m}\ d\text{Å}$
400	73	2.90	16	4.00	11.60
420	100	2.58	20	4.47	11.53
332	10	2.47	22	4.69	11.58
422	48	2.35	24	4.90	11.52
510	14	2.27	26	5.10	11.58
521	12	2.11	30	5.48	11.56
440	3	2.04	32	5.66	11.55
611	13	1.83	38	6.16	11.58
620	4	1.83	40	6.32	11.57
444	16	1.67	48	6.93	11.57
640	23	1.60	52	7.21	11.54
642	48	1.54	56	7.48	11.52
842	11	1.26	84	9.17	11.55

Sum of a_o's = 150.25

Average a_o = 11.56 Å

EXPLANATION OF TABLE III

X-ray data and a_0 calculation for magnetite.

TABLE III

hkl	Intensity	$d\mathring{A}$	$m=h^2+k^2+l^2$	$\sqrt{m}$	$a_o=\sqrt{m}\ d\mathring{A}$
111	13	4.85	3	1.73	8.39
220	33	2.97	8	2.83	8.41
311	100	2.53	11	3.32	8.40
400	29	2.10	16	4.00	8.40
422	12	1.71	24	4.90	8.38
333	26	1.62	27	5.20	8.42
511	26	1.62	27	5.20	8.42
440	25	1.48	32	5.66	8.38
533	9	1.28	43	6.56	8.40

Sum of a_o's = 75.60

Average a_o = 8.40 $\mathring{A}$

EXPLANATION OF TABLE IV

X-ray data and a_o, c_o calculations for ilmenite.

TABLE IV

hkl	Intensity	dÅ	log dÅ	x*	$\frac{1}{2}$ log x	log a_o*
102	24	3.73	0.572	1.85	0.134	0.706
104	100	2.74	0.438	3.42	0.267	0.705
110	35	2.54	0.404	4.00	0.301	0.705
113	27	2.23	0.348	5.17	0.357	0.705
204	24	1.86	0.270	7.42	0.435	0.705
116	47	1.72	0.236	8.69	0.461	0.705
108	11	1.62	0.210	9.67	0.493	0.702
214	26	1.50	0.176	11.42	0.529	0.705
300	19	1.46	0.164	12.00	0.540	0.704

Sum of log a_o's = 6.34 $c_o = c\ a_o$

Average log a_o = 0.704 $c_o = (2.77)\ (5.06)$

$a_o = 5.06$ Å $c_o = 14.00$ Å

*$x = 4/3\ (h^2 + hk + k^2) + l^2/c^2$

* log $a_o = $ log dÅ $+ \frac{1}{2}$ log x

EXPLANATION OF TABLE V

X-ray data and dÅ for serpentine compared with ASTM standard dÅ for lizardite.

EXPLANATION OF TABLE VI

X-ray data and dÅ for mica compared with ASTM standard dÅ for chlorite.

TABLE V

hkl	Intensity	dÅ	dÅ ASTM
001	100	7.36	7.36
020	26	4.58	4.62
021	10	3.91	3.89
002	55	3.66	3.64
201	43	2.50	2.50
202	13	2.15	2.15
203	12	1.80	1.79
060	33	1.54	1.53
204	12	1.50	1.50
401	10	1.31	1.31

TABLE VI

hkl	Intensity	dÅ	dÅ ASTM
001	96	14.4	14.5
002	100	7.26	7.16
003	95	4.83	4.80
004	97	3.64	3.55
005	81	2.91	2.86

APPENDIX II

The flux monitor (standard) was made with the following elements and concentrations of each: La- 19.30 μg/ml, Sc- 1.21 μg/ml, Tb- 0.83 μg/ml, Ho- 0.103 μg/ml, Sm- 0.925 μg/ml, Eu- 0.196 μg/ml, Dy- 0.509 μg/ml, Th- 0.506 μg/ml, Ce- 17.79 μg/ml, Nd- 14.31 μg/ml, Yb- 1.82 μg/ml, Lu- 0.43 μg/ml, Ta- 0.95 μg/ml, Zr- 201.63 μg/ml, Na- 470.8 μg/ml, K- 5.663 mg/ml. One milliliter of each was placed in the flux monitor.

Because of the complexity of the kimberlite whole rock spectra, only La, Sc and Sm could be determined quantitatively. Most of the other elements in the flux monitor were observed.

Calculation of the abundance of an element in the kimberlite which is in the flux monitor, is accomplished with the following formula: $C_r^* = \left(\dfrac{A_r^*}{A_{fm}^*}\right) C_{fm}^*$ / sample weight, where C_r^* = concentration of isotope in the rock, C_{fm}^* = concentration of same isotope in the flux monitor, A_r^* = area under peak of the same isotope in the whole rock spectrum and A_{fm}^* = area under the same peak of the same isotope in the flux monitor spectrum. Sample weight = 100.1 g.

Calculation illustration:

$$La_r^{140} = \frac{\left(\dfrac{3155}{794}\right) 19.50 \ \mu g/ml}{100.1 \ \mu g} = 0.7742 \ \mu g,$$

$$0.7742 \ \mu g = 774.2 \ ppm.$$

Note: Peak areas are computed from the paper tape read-out of the various spectra.

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PETROLOGY OF THE
LEONARDVILLE KIMBERLITE

by

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B. S., OLD DOMINION COLLEGE, 1967

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Geology

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1970

ABSTRACT

Of the six kimberlites known in Riley County, Kansas, the Leonardville kimberlite was selected for study because of lack of prior work.

The Leonardville kimberlite intrudes Lower Permian sedimentary rocks; forms a slight topographic high, and its magnetic direction is approximately normal to the axis of the Abilene Anticline.

The Leonardville kimberlite is a medium-grained intrusive kimberlite breccia. Most inclusions consist of country rocks but two igneous inclusions were also noted. The minerals at Leonardville are: serpentinized olivine and pyroxene, severely altered biotite or phlogopite, garnet (50 percent pyrope, 30 percent almandine, 20 percent grossularite), ilmenite, magnetite, hematite, lizardite, vermiculite, calcite, barite and possibly perovskite pyrite, zircon, chromite, apatite and dolomite.

Analytical techniques used were: polarizing microscope, x-ray diffraction and fluorescence, neutron activation analysis and mass spectrometry.

Purple garnets have an index of refraction of 1.755 and a unit cell of 11.58 $\mathring{A}$ and the orange-yellow garnets have an index of refraction of 1.750 and a unit cell of 11.56 $\mathring{A}$. Magnetite has a unit cell of 8.40 $\mathring{A}$, and a density of 5.18. Ilmenite has the following unit cell: $a_o = 5.06 \mathring{A}$, $C_o = 14.0 \mathring{A}$ and has a density of 4.39. Lizardite has $C_o = 7.36 \mathring{A}$. Mica has $C_o = 14.4 \mathring{A}$. Neutron activation analysis of the whole rock revealed 774 ppm La, 19 ppm Sc and 13 ppm Sm and Tb, Na, Mn, Pb, Eu, Fe, Cr, V, K and Co. Whole rock Sr content is estimated at 1000-1500 ppm. The whole rock Sr^{87}/Sr^{86} ratio is 0.709, a composite garnet Sr^{87}/Sr^{86} ratio is 0.7076 and a vein calcite is 0.7043.

The Leonardville kimberlite's earliest origin can be traced to a minimum depth of 40-50 kilometers at which time the garnets were formed. Serpentinization began in the lower crust, 20-30 kilometers below the surface and occurred

at least twice and with contemporaneous formations of magnetite. Once into the Paleozoic sedimentary sequence, numerous inclusions of country rock were incorporated into the kimberlite. Existing joint patterns controlled final emplacement, during the late Cretaceous at low temperatures in the range of 75°-150° C.