MINERALOGY AND PETROGENESIS OF THE STOCKDALE INTRUSION, RILEY COUNTY, KANSAS

by

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INTRODUCTION

General Statement

Stockdale is one of five ultrabasic igneous intrusions that occur in Riley County, Kansas. These intrusions crop out in an area of lower Permian sedimentary rocks; and are named as follows: Stockdale, Bala, Leonardville, Randolph No. 1 and Randolph No. 2.

The Stockdale intrusion outcrops as a topographic low, on a stream bed. It is located on the SE 1/4 SW 1/4 NE 1/4 and the NE 1/4 NW 1/4 SE 1/4, Section 23, T. 8 S., R. 6 E. (Plate I).

The outcrop of the intrusion, partly covered by vegetation and alluvium, has a highly irregular outline. Only part of the contact between the intrusion and the intruded country rock is recognized in the field. The entire contact can be approximated by the use of the joint pattern in the intrusion or by the zone of sharp magnetic gradient in the vicinity of the +1000 gamma contour as mapped by Cook (1955). Earlier magnetic investigations in the area also showed that the Stockdale intrusion is a nearly vertical body plunging to the Southeast.

All five intrusions in Riley County occur along jointological anomalies. Nelson (1952) noted that there seems to be a definite relationship between the location of the intrusions and the number of joints per unit area. He also points out that the intruding bodies do not occur where the number of joints is either too high or too low, but rather in intermediate zones.

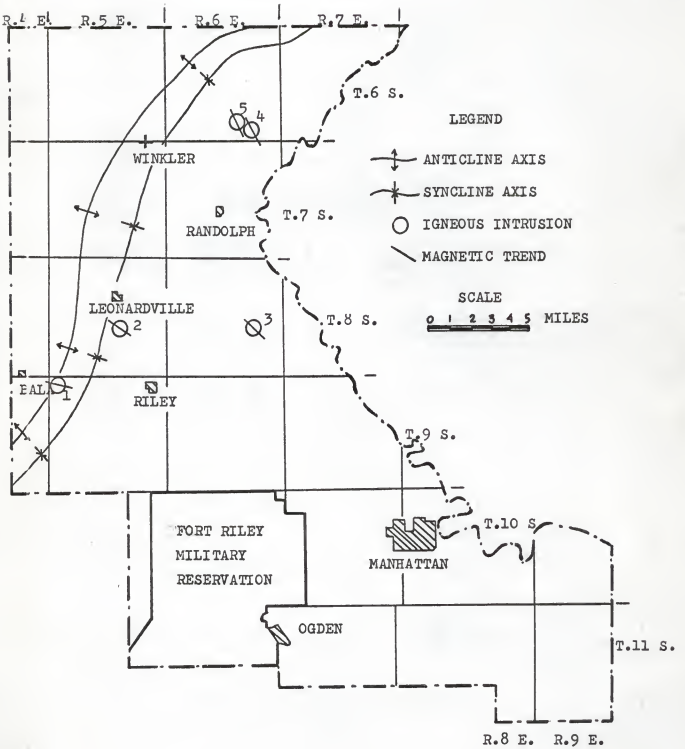
Due to the facts that erosional pieces of the intrusion can be found both upstream and downstream and that the stream bed where the Stockdale intrusion outcrops shows evidence of stream flow reversal raises the possibili-

EXPLANATION OF PLATE I

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

1. Bala Intrusion
2. Leonardville Intrusion
3. Stockdale Intrusion
4. Randolph No. 1 Intrusion
5. Randolph No. 2 Intrusion

PLATE I


R.4 E.
R.5 E.
R.6 E.
R.7 E.
T.6 S.
T.7 S.
T.8 S.
T.9 S.
T.10 S.
T.11 S.
R.8 E.
R.9 E.
WINKLER
RANDOLPH
LEONARDVILLE
RILEY
MANHATTAN
OGDEN
FORT RILEY
MILITARY
RESERVATION
LEGEND
ANTICLINE AXIS
SYNCLINE AXIS
IGNEOUS INTRUSION
MAGNETIC TREND
SCALE
0 1 2 3 4 5 MILES

ty of emplacement along the plane of a fault with slight hinge and strike-slip movements. Nevertheless, evidence of such faulting is not found in the field.

Previous Investigations

Published Data. Byrne, Parish and Crumpton (1956) summarized the most important physical features of the five intrusions in Riley County, Kansas. They suggested that the probable time of intrusion was Late Cretaceous. This will be discussed in detail later.

Jewett (1941) has described the geology of Riley and Geary Counties, and the geology of the Abilene Anticline was discussed by Shenkel (1959).

Cook (1955) investigated the Leonardville, Randolph No. 1, Randolph No. 2 and Stockdale intrusions magnetically. Vertical magnetic intensity maps and the results of the magnetic survey indicated that the intrusions were nearly vertical bodies with a Southeast plunge.

Eastwood and Brookins (1965) studied trace element variation in the Stockdale and Bala intrusions by emmission spectrography.

Unpublished Data. A general study of the joint systems of Riley County was conducted by Neff (1949). The geology of Riley County, Kansas and associated structures were studied by Beck (1949), Baysinger (1963), Koons (1955), Merryman (1957) and Rosa (1963).

Nelson (1952) made a study on the reflection of the basement rocks in the surface structures of Marshall and Riley Counties, Kansas. A study of the possible origin of the intrusions was included in his investigation. He attributed the origin of the intrusions to a momentary opening of the joints

caused by local releases of pressure, permitting the magma to flash into the openings and then the joints were immediately "slammed shut" thus causing the oval-shaping of the intrusions.

Bridge (1953) investigated all five intrusions in the light of obtaining information about the relationship between the inclusions found in the serpentine plugs and the groundmass. He attributed the serpentinization to internally derived water which acted as a lubricating mechanism during a late magmatic stage.

Taylor (1950) discussed the general magnetic outlines of three of the intrusions in Riley County and attempted to determine their possible origin. He explained the emplacement of the intrusions by zones of weakness in gash-fractures produced by strike-slip movement along the Abilene Arch.

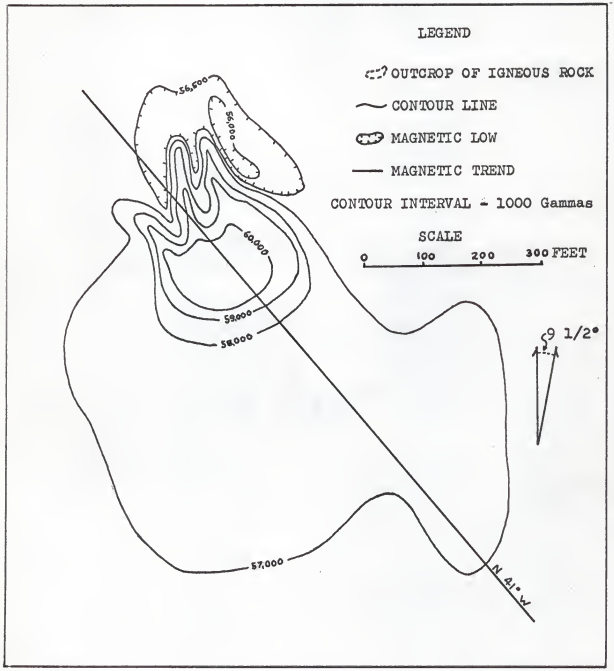
Dowell (1964) conducted a magnetic survey of the five known ultrabasic intrusions in Riley County with a M-49A Varian portable magnetometer. He found a positive anomaly greater than 4,000 gammas and a highest total magnetic intensity reading of 60,930 gammas over the Stockdale intrusion. The total magnetic anomaly associated with the intrusion was approximately 1,000 feet long and 850 feet wide. Its magnetic trend is N 41 W (Plate II).

Eastwood (1965) investigated the Bala and Stockdale intrusions by emission spectrography. He states in his conclusions that the Stockdale intrusionrepresents rocks that have experienced some differentiation prior to/or concurrent with the time of injection. He also concluded that serpentinization occurred during injection in an essentially closed system. Part of this thesis has been published (Eastwood and Brookins, 1965).

EXPLANATION OF PLATE II

Magnetic map of the Stockdale intrusion, (modified from Dowell, 1964).

PLATE II


LEGEND
OUTCROP OF IGNEOUS ROCK
CONTOUR LINE
MAGNETIC LOW
MAGNETIC TREND
CONTOUR INTERVAL - 1000 Gammas
SCALE
0 100 200 300 FEET
54,000
55,000
60,000
59,000
58,000
57,000
9 1/2°
N 41° W

Method of Study

The outcrop of the Stockdale intrusion was examined and mapped. Samples were collected in the field and prepared and studied in the laboratory.

Mapping Procedures. The outcrop of the intrusion was mapped in the field with the use of a plane table, Brunton compass, and measuring rod. Strike and dip of the exfoliation and joints were included in the map. A faint color difference noted on concentric rings was also included.

Sampling Procedures. Fresh samples were obtained in the field with the aid of a chisel, hammer, and sledge hammer. The weathered zone was removed and the samples were collected from the bedrock six inches from any contaminated rock. Calcite seams, highly calcareous zones and noticeable large inclusions of calcareous country rock were avoided in order to lessen calcium contamination of the samples.

Laboratory Study. The samples brought to the laboratory were washed, crushed, sieved and portions of the sieved fractions were treated with glacial acetic acid.

Mineral separation was accomplished by the use of the Frantz Isodynamic magnetic separator, heavy liquids and decantation. Hand picking under binocular microscope directly from the rock fragments helped the purification of some of the mineral separates.

The pure mineral separates were studied by X-ray diffraction, index of refraction, and gravity measurements. (Details of this study are presented in the section on analytical procedures).

GEOLOGY

Stratigraphy

Precambrian Rocks. Precambrian rocks do not crop out in Riley County, Kansas but are extensively known from well data. Many wells have penetrated the Precambrian basement rock complex which has been found to be deepest at about 9,500 feet in the Hugoton Embayment, and shallowest at about 600 feet over the Nemaha ridge in northeastern Kansas.

The Precambrian rocks in the area of the Abilene Anticline consist of schist, quarzite, granite and granite gneiss. Well cuttings from a well drilled into the Precambrian rocks near Clay Center have been identified as diabase by Farquhar (1957).

A weathered zone of detrital material known as "Granite Wash" covers large areas of the Precambrian complex beneath Paleozoic rocks, (Merriam, 1963). In northeastern Kansas this layer actually corresponds to weathered granite which overlies the unweathered Precambrian surface.

J. L. Kulp of the Lamont Geological Observatory of Columbia University determined Potassium-Argon ages of five samples of Precambrian complex from Barton, Rush and Morris Counties, Kansas. The ages obtained range from 1,165 to 1,460 million years, which are comparable to Precambrian ages found elsewhere in central United States, (Merriam, 1963).

Paleozoic Rocks. Paleozoic rocks nonconformably overlie the Precambrian everywhere in Kansas. They are exposed at the surface in the area of investigation and are unconformably overlain by Mesozoic and Cenozoic rocks to the west.

The oldest rock outcropping in Riley County, Kansas is Pennsylvanian in

age. A few feet of Cretaceous sandstone occur in northwestern Riley County. The surface rocks as a whole, however, consist principally of Permian sedimentary rocks.

A typical columnar section of the sedimentary sequence was presented by Shenkel (1959) from the Llewelyn No. 1 well (NE 1/4 NE 1/4 NE 1/4, Section 11, T. 9 S., R. 4 E.) in Riley County. Shenkel found the Arbuckle group to be less than 30 feet thick. He described it as consisting of cherty dolomitic limestone of Late Cambrian to Early Ordovician age lying nonconformably on Precambrian rocks. Middle Ordovician to Late Mississippian rocks make up approximately 890 feet of the section. These are composed primarily of cherty and shaly dolomites with minor sandstone (St. Peter: Middle Ordovician) and shale (Chatanooga and Boice: Devonian and Mississippian respectively). Pennsylvanian and Permian rocks are represented by 1.900 feet of alternating shales and limestones.

Cenozoic Stratigraphy. The only Cenozoic rocks found in the area consist of loess deposits which are a few feet thick. Relatively thick deposits of glacial origin, restricted to the northeastern parts of Kansas, are composed of glacial till (Kansan and Nebraskan age) and glacial outwash. The thickness of any of these Pleistocene sediments does not exceed more than a few feet in the immediate vicinity of the intrusion.

Structure

Regional Structure. The consolidated rocks are structuraly included in the Prairie Plains monocline, (Jewett, 1941).

The area where the Stockdale intrusion outcrops is on the eastern flank

of the Salina basin which is separated from the Forest City basin to the east by the Nemaha Anticline and is bound to the west by the Central Kansas Uplift.

The axis of the Salina basin parallels the Central Kansas Uplift in a northwestward trend. The axis of the Nemaha Anticline trends N 20° E through the area of investigation.

Local Structures. The only major structure in the area is the Abilene Anticline which trends northeast-southwest and extends 70 miles from an area near Abilene to an area south of Marysville, Kansas. The axis of the Abilene Anticline intersects the west flank of the Nemaha Anticline near the Kansas-Nebraska border in Marshall County, Kansas, (Shenkel, 1959).

Another structure, the Irving Syncline occurs between the Abilene Anticline and the Nemaha Anticline and its axis parallels the axis of the Abilene Anticline.

Structural History. Lee (1956) described the structural history of the Salina basin and recognized five periods of regional deformation affecting the development of this area. These periods are: the pre-St. Peter deformation, the post-St. Peter pre-Chattanooga deformation, Early Mississippian through Permian deformation, post-Permian pre-Cretaceous deformation and the post-Cretaceous deformation.

In pre-St. Peter time the Southeast Nebraska Arch was deformed. A northwest trending syncline started to develop to the southwest of the Southeast Nebraska Arch across part of the area that later was to become the Central Kansas Uplift.

During the second period of deformation, the Southeast Nebraska Arch sub-

sided to the North Kansas Basin. The initial structural development of the Central Kansas Uplift, the Chautauqua Arch and the Hugoton Embayment were contemporaneous events which occurred during this time.

The deformation of the Nemaha Anticline, the Abilene Anticline and the Central Kansas Uplift began in Early Mississippian time, reached its climax at the end of the Mississippian and continued until Middle Permian time with decreasing strength. During Early Mississippian time regional tilting to the north occurred, and the area was tilted to the south by late Mississippian time.

The deformation of the Central Kansas Uplift which began in Early Mississippian time culminated at the end of the Permian period. The tilting of the Central Kansas Uplift to the southwest toward the Hugoton Embayment followed.

The post-Cretaceous deformation caused the tilting of the region northward and northwestward toward the Denver basin. The net result of the tilting is observed on the northwestward regional dip of the stratigraphic units in the Salina basin.

PETROGRAPHY AND PETROLOGY

Outcrop Description

The Stockdale intrusion crops out as a topographic low on a stream bed. The outline of the outcrop is highly irregular and its extension is limited by the amount of vegetation and soil that surround and cover it. The bedrock does not bear any soil nor does it support any vegetation. The shape of the plug is elongated in a north-south direction.

The outcrop occurs 0.30 miles west of the east end of the east-west line that bisects the section extending approximately 80 feet to the north

of this line through Section 23, T. 8 S., R. 6 E., and 125 feet to the south of the same line. The outcrop is approximately 130 feet wide in the east-west direction (Plate III).

The surface of the outcrop presents some exfoliation presumed to be parallel or subparallel to the roof of the intrusion. The numerous joints and fractures that cut it are not continous with the joints in the country rock around the plug. Two sets of joints cut the intrusion: one of random orientation and another of radial distribution (see Plate III). Both have been filled by calcite and are easily detected.

The contact effects and the contact metamorphism can be studied only in the stream bed where two or three feet of the contact is visible during dry spells. The impregnation of the limestone with which the intrusion is in contact at this point is slight and the indurated zone is only 2-3 inches thick.

The Stockdale intrusion cuts the Fort Riley limestone at the point of contact. The Fort Riley limestone belongs to the Barneston formation, Chase Group, Wolcamp Series, Permian System. The stratigraphic unit that forms the slopes on both sides of the intrusion is the Holmesville shale of the Doyle formation, Chase Group, Wolfcamp Series, Permian System. The Towanda limestone caps the hills on each side of the stream and about 27 feet above the intrusion (Jewett, 1941).

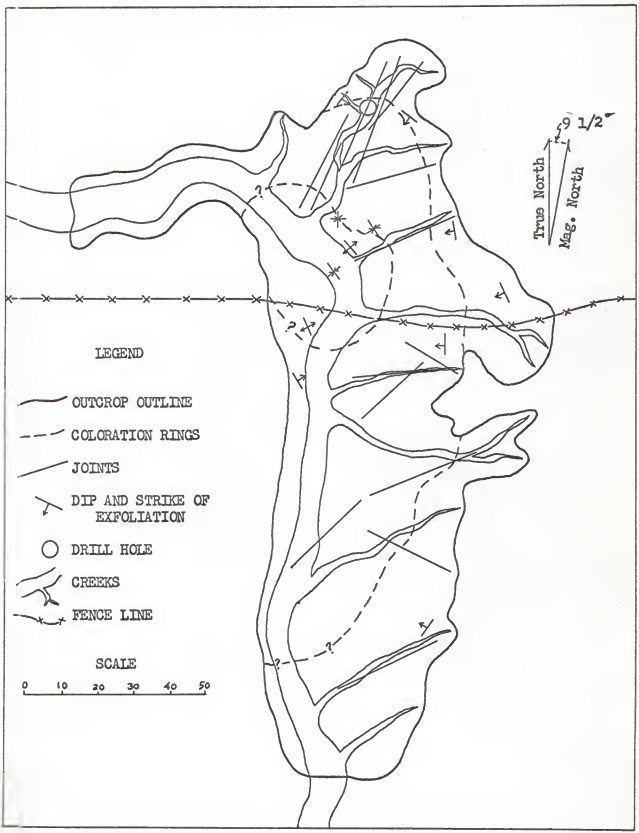
Hand Specimen Description

A typical specimen consists of a light to dark green, fine-grained groundmass containing many xenoliths and inclusions of igneous, metamorphic and neighboring sedimentary rocks. Numerous inclusions produce a highly

EXPLANATION OF PLATE III

Outcrop map of the Stockdale intrusion showing the joint pattern, dip and strike of exfoliation and rings of coloration.

PLATE III


9 1/2°
True North
Mag. North
LEGEND
OUTCROP OUTLINE
COLORATION RINGS
JOINTS
DIP AND STRIKE OF EXFOLIATION
DRILL HOLE
CREEKS
FENCE LINE
SCALE
0 10 20 30 40 50

brecciated appearance. Phenocrysts and xenocrysts of mica, garnet, magnetite and ilmenite give the rock a porphyritic texture. Numerous veins and pockets of calcite ranging in size from microscopic dimensions to one and a half inch in width fill the fractures that cut the Stockdale intrusion.

Thin Section Study

General Statement. Ten thin sections were studied with the aid of a petrographic microscope. A mineral count was made on each slide. The results of the mineral counts are given in Table I. The mineral-to-mineral contacts were also studied and are presented in Table II.

Mode of Occurrence. Red pyrope occurs as discrete pale pink to blood red, rounded nodules with numerous fractures filled with calcite and/or serpentine. A kelyphitic rim may be present around each individual grain, but commonly has been stripped off during emplacement. This rim is made up of chrysotile. The red pyrope ranges from a fraction of a millimeter to two centimeters in diameter.

Green pyrope is not easily seen either in hand specimen or in thin section. Due to its color, appearance and amount of alteration, it is easily confused with the minerals of the groundmass. Its mode of occurrence, therefore, is not clearly defined but it usually occurs as subhedral to euhedral, light to dark green, fairly well altered grains disseminated throughout the groundmass. The size of the green pyrope is usually small, less than 4-5 millimeters in diameter.

The separated grains of the green pyrope were observed to change color under various types of illumination. Changes in color with change in illumination were observed as follows: in natural light this pyrope is green and

EXPLANATION OF TABLE I

Mineral table showing individual percentages of minerals for each thin section studied, and average values for ten thin sections.

TABLE I

Mineral	Thin Sections										
	S-1a	S-1b	S-2	S-3a	S-3b	S-4	S-7	S-8	S-9	S-10	Average
Antigorite	41	38	42	43	42	44	42	44	36	20	39.2
Pyroxene	10	9	7	11	6	6	6	5	6	10	7.6
Olivine	4	3	4	5	4	2	4	3	3	3	3.5
Perovskite	3	4	6	3	3	3	6	4	8	5	4.5
Magnetite	6	8	6	5	13	5	4	7	4	6	6.4
Hem-Limonite*	T*	T	T	T	T	T	T	T	T	T	T
Ilmenite	5	4	2	3	3	3	2	3	4	4	3.3
Leucoxene	T	T	T	T	T	T	T	T	T	T	T
Chlorite	4	5	8	5	5	4	5	5	7	6	5.4
Phlogopite	T	1	T	T	1	1	T	1	T	1	0.8
Biotite	-	T	T	-	T	-	-	-	-	-	0.1
Green Pyrope	2	2	1	1	1	3	2	1	1	2	1.6
Red Pyrope	-	2	2	1	1	5	2	2	1	6	2.2
Chrysotile	T	T	T	T	T	1	T	T	T	1	0.6
Calcite	20	19	15	20	16	21	22	20	24	20	19.7
Chromite	T	T	T	T	T	T	T	T	T	T	T
Rutile	T	T	T	T	T	T	T	T	T	T	T
Quartz	T	T	T	T	T	T	T	T	T	T	T
Chalcedony	T	T	T	T	T	T	T	T	T	T	T
Silica	T	T	T	T	T	T	T	T	T	T	T

Hem-Limonite* indicates Hematite - Limonite

T* indicates Trace, less than 0.8%

Table II. Mineral-to-mineral contacts in the Stockdale intrusion.

	Ilmenite	Ch. Phlog*	Red Py*	Green Py*	Pyxene*	Olivine
Ilmenite	XX	XX	XX	XX	XX	XX
Ch. Phlog.	XX	XX			XX	XX
Red Py.	XX		XX		XX	XX
Green Py.	XX			XX	XX	XX
Pyxene.	XX	XX	XX	XX	XX	XX
Olivine	XX	XX	XX	XX	XX	XX

Ch. Phlog* indicates chloritized Phlogopite; Red Py* indicates Red pyrope; Green Py* indicated green pyrope; Pyxene* indicates Pyroxene.

and under artificial light, red. The phenomenom observed is similar to that for alexandrite; and evidently has the same cause, (Smirnov, 1959).

Chrysotile occurs as kelyphitic rims around some of the red pyrope grains and rarely as small patches in contact with a few green pyropes. These rims probably represent post-crystallization reaction between the garnets and the liquid. If this is the case, the rims would signify an earlier crystallization of the red pyrope relative to the green.

The chrysotile occurs as pale brown needle-like crystals a few microns across and up to one half millimeter long that radiate out from the garnets into the surrounding groundmass.

Magnetite occurs as discrete black crystals up to two centimeters in diameter and as small crystals and inclusions disseminated throughout the groundmass, inside of/ and as replacement of other minerals, sometimes only a few microns across. Most of the large grains show crystal faces and a few occur as perfect twinned crystals.

Both hematite and limonite are always found associated with magnetite and

occur as its alteration product. Hematite is recognized by its characteristic reddish color and limonite by its yellow brown coloration. Limonite is by far the most abundant of the two and is seen in thin section as alteration products around magnetite grains or as irregularly shaped clusters. Hematite occurs as very thin alteration rims around some of the magnetite grains.

Ilmenite occurs as discrete irregularly shaped black grains almost invariably coated by an alteration rim of leucoxene. The ilmenite varies from a fraction of a millimeter to one and one half centimeters in diameter and is easily distinguished from magnetite by the presence of leucoxene rimming the former.

Leucoxene occurs as a very light green to gray microcrystalline alteration product of ilmenite elther as a rim or filling small fractures within the grain.

Although original phlogopite has been highly chloritized, the preservation of some of the original mineral is indicated by zones of high birefringence. It shows undulatory extinction.

Chlorite is found as an alteration product of phlogopite and as reaction rims around olivine, pyroxene and green pyrope. As in alteration rims, it occurs as bright green microcrystalline bands up to a few millimeters thick around the minerals from which it resulted. As the chloritization product of phlogopite it is found as discrete, yellow to pale brown mica books up to one and a half centimeters across and 3/4 centimeters thick. The chlorite found in these books has been partly replaced by calcareous material (two generations), and by siliceous material of secondary origin.

Diopside was by far the most abundant of the pyroxenes present in the slides studied. Identification of other clinopyroxenes or orthopyroxenes in minor abundance was difficult due to the high degree of alteration and

serpentinization. Diopside occurs as anhedral to subhedral, well altered, pale to dark green grains. Pure diopside is absent from the rock and the degree of alteration varies from slight to complete replacement. The alteration products are serpentine minerals, chlorite, silica and rarely perovskite. The pyroxenes vary from a fraction of a milimeter to almost 2 milimeters across, some of which show good crystal faces.

By petrographic evidence the olivine present seems to be closer to the forsterite end member than to the fayalite end member in composition. It occurs as individual, translucent, pale to medium green, anhedral well altered grains. The olivines vary from a fraction of a milimeter to several milimeters across and are almost invariably rimmed by their alteration products: chlorite and in some instances, perovskite and silica. Fawcett (1965) found the same alteration products for olivine and pyroxene in basalts.

Antigorite and other serpentinization minerals are common. Of these the most abundant mineral in the rock is antigorite. These minerals are found as the alteration products of olivine and pyroxene which are disseminated through out the groundmass. Antigorite and the other perpentine minerals are recognized in thin section as microcrystalline, light to dark green minerals.

Perovskite has two modes of occurence: one as alteration rims around a few pyroxene and olivine grains; and as discrete, characteristically green to light brown crystals less than one milimeter across.

Biotite is one of the minor constituemts of the rock and its presence is rare. When present, it occurs as euhedral, well defined characteristically dark brown books of mica a few tenths of a milimeter across.

Quartz occurs as subhedral grains replacing the mica and other minerals. It is slightly fractured ans shows undulose extinction.

Chalcedony occurs in vein fillings which cut the groundmass and the minerals. It is probably the result of subsurface water permineralization.

Silica is found in rims of alteration products around some pyroxene and olivine grains. Its occurrence is rare.

Chromite occurs as subhedral to euhedral discrete grains disseminated in the groundmass. It is present only in trace amounts.

Rutile is found as minute needles only a few microns in length included in other minerals and in the groundmass.

Petrology

The original olivine-pyroxene rich magma (from petrographic evidence) can be classified as ultramafic in composition. Bridge (1953) attributed the serpentinization to internally derived water which acted as a lubricating mechanism during emplacement. Eastwood (1965) suggested that the serpentinization could have occured as late as post-emplacement as caused by the action of ground water. There is little evidence of such late serpentinization as indicated by the well preserved inclusions.. Furthermore, there is evidence(presented in the discussion section of this paper) that indicates pre-emplacement serpentinization.

The manner of occurrence of the inclusions and the slight contact effects suggest a low temperature of intrusion. Bowen and Tuttle (1949) state that injection of a peridotite magma in a aqueous environment could occur at temperatures as low as 400°C. Evidence based on the Potassium-Argon age work presented later in this paper indicates an even lower temperature of intrusion, in the vicinity of 200°C. This low temperature intrusion would have occurred in a plastic "mush" state in which most of the minerals crystallized before final emplacement.

Garnet, ilmenite, magnetite and the chloritized phlogopite were the only minerals that escaped complete serpentinization. Table I contains petrographic data and estimates of the relative amounts of the minerals in the described sample.

ANALITICAL PROCEDURES

Sample Preparation

Preliminary Preparation. The sample pieces were washed with tap water and brush, rinsed with demineralized water, and dried with acetone. They were allowed to dry overnight.

Grinding Procedures. The samples were crushed in a jaw crusher and in a disk grinder. The ground sample was sieved for 30 minutes in a shaker using 40, 100, and 200 mesh sieves. In this manner the sample was separated into four size fractions: +40, -40:+100, -100:+200, and -200. The fractions were stored in bottles previously washed with soap and water followed by rinsing with 2N vycor distilled hydrochloric acid, demineralized water, and acetone. The bottles were covered with parafilm and stored in a dry, clean place until further use.

Acid Treatment. To avoid contamination of the mineral separates with calcite during this investigation, each portion of the sample was treated with glacial acetic acid. This was accomplished by dividing the sample into 300 gram fractions. These fractions were put in one-gallon jars and moistened with distilled water. Three normal 99% pure glacial acetic acid was added and this mixture was stirred occassionally. Small quantities of acid were added to maintain the pH of the mixture at 3-4.

At the end of 24 hours the sample was washed for two hours with tap

water followed by rinsing with demineralized water and acetone. When dry, the sample was found to be Calcite-free.

Mineral Separation

Magnetite-Ilmenite. These minerals were the first to be separated. The preliminary separation was accomplished with a hand magnet warpped in clean weighting paper.

The highly magnetic fraction obtained in this manner was separated into 20 gram fractions and treated with vycor destilled 6N hydrochloric acid for 24 hours. This time was found to be sufficient to partly decompose some of the mafic minerals intergrown with the magnetic minerals. Both minerals were further concentrated by hand panning.

The magnetite and ilmenite were separated from each other by the use of the Frantz Isodynamic Magnetic separator. Two settings were used, No. 1a and 2a (Table III.). In the separation No. 2a, using the non-magnetic fraction of separation No. 1a, the setting was repeated five times until the ilmenite in the non-magnetic side was 99+% pure.

The magnetite from separation No. 1a and the ilmenite from No. 2a thus obtained were used for futhere studies.

Red and Green Pyropes. The separation of these two minerals from the whole rock was accomplished in several steps, using both the Frantz Isodynamic Magnetic separator and heavy liquids.

Bromoform heavy liquid with density equal to 2.625-2.687 was used for the first step of the separation, (Table IV.). This permitted the red and green pyropes, ilmenite, some mica and olivine to be obtained as the heavy fraction. This heavy fraction was put through the Frantz at setting No. 3a

(see Table III.), obtaining separates No. IIIa and IVa. The ilmenite in sample Ib was the most magnetic mineral in the separate and was attracted by the magnet at setting 3a. After the garnets were removed form the collecting cups, the current was switched off and pure ilmenite was collected. The red and green garnets obtained were 85% pure.

The separation of the green from the red garnet was accomplished by the use of repeated runs through the Frantz. After separations at settings 4a, 5a, and 6a (see Table III.), the final red and green separates VIIIa and Xa were purified by hand picking the impurities.

Red Garnet Impurities. Due to the small amount of red pyrope obtained from previous separations, hand picking directly from the rick sample was necessary. During this procedure it was possible to separate the impurities and alteration products of the red pyrope by size.

Chloritized Phlogopite. The perliminary separation of this mineral was first attempted by Bromoform treatment. The heavy fraction IIIb (see Table IV) obtained was purified by hand picking. The amount of pure mineral obtained from this method was found to be insufficient, and therefore separation of the mica directly from the rock samples became necessary. Using this technique close to 20 grams of pure mineral separate were collected in a relatively short time.

Other Preliminary Studies

Index of refraction measurements were made on the red and green pyropes. The index of the red garnet was found to be 1.747, that of the green garnet 1.753. Both measurements were made using the oil immersion method.

The specific gravity of magnetite and ilmenite were measured with a Jolly Balance. A value of 5.13 g/cc was found for magnetite and a value of 4.57 g/cc for ilmenite.

EXPLANATION OF TABLE III

Mineral separation settings in the Frantz Isodynamic Magnetic Separator.

EXPLANATION OF TABLE IV

Heavy liquid mineral separations.

TABLE III

Setting Number	Sample	Size Fraction	Non Magnetic	No.	Magnetic	No.	Side Slope	Forward Slope	Amps.
1a	IlmMag*	40-100	Ilm+Mag.	Ia	Mag.	IIa	5	15	0.00
2a	Ia	40-100	Ilm pred*	-	Ilm+Mag.	-	20	15	0.05
3a	Ib	40-100	Mafics	IIIa	Garnets	IVa	30	30	0.90
4a	IVb	40-100	Red Gar.*	Va	Gr. Gar.*	VIa	25	15	0.74
5a	Va	40-100	Imp.*	VIIa	Red Gar.	VIIIa	24	30	0.89
6a	VIa	40-100	Imp.	IXa	Gr. Gar.	Xa	24	30	0.90

IlmMag* indicates Ilmenite and Magnetite

Ilm pred* indicates Ilmenite predominant

Red Gar.* indicates Red Garnet predominant

Gr. Gar.* indicates Green Garnet predominant

Imp.* indicates impurities

TABLE IV

Separation Number	Sample	Size Fraction	Heavy Fraction	No.	Light Fraction	No.	Liquid Used	Density
1b	Whole Rock	40-100	Garnets, Ilm+Oli.*	Ib	Mafic Mins.	IIb	Bromo-form	2.625-2.687
2b	IIIa	40-100	Mica + Olivine	IIIb	Mafics	IVb	Bromo-form	2.848-2.925

Ilm+Oli.* indicates Ilmenite and Olivine

X-RAY PROCEDURES

Introduction

Several pure mineral fractions were prepared to be studied from their X-ray diffraction patterns. Several mountings were prepared for both the green and red garnets. During the course of the mineral separation, it was possible to separate a relatively pure fraction of the alteration products of the red garnet. This fraction was also mounted ans studied by X-ray diffraction.

Several slides were prepared for ilmenite and magnetite. The mica was separated into two aliquots, one was treated with glacial acetic acid for 24 hours to remove the calcite in the sample. Both of these samples were mounted and analyzed.

Two standards, one for uvarovite and one for silicon, were analyzed for comparison purposes.

X-ray Investigation

The instruments used in this part of the investigation were: an X-ray generator and diffractometer, a goniometer, and a control panel all produced by the Norelco Division of Phillips Electronics Instruments. A Minneapolis Honeywell recorder was used.

The settings were common to all samples studied except for the scale factor which was varied to achieve the best background-peak ratio for each individual aliquot. The following settings were used;

Diffractometer: 38 Kilovolts, 18 Miliampers, Cu Kα radiation.

Diffractometer: Divergent slit 1°, Receiving slit 0.006 inches, Antiscatter slit 1°.

For the Control Panel:

Kilovolt range 1=0.68-0.85 Kilovolts.

Kilovolt range 2=1.4-1.7 Kilovolts.

Detector 2 Voltage = 1.7 Kilovolts.

Length = 9.0 Volts

Width = 9.0 Volts

Multiplier switch = on 10 position

Seconds-Count switch = on 1,000.0 sec. -10^6 counts position

Lin-Log switch = in Linear position

Function Selector switch = in Continous count position

Input Selector switch = in Gas Flow position

Width switch = in Differential position

Time Constant = 2 Seconds

Scale Selector = determined by the nature of the sample studied.

The results were recorded at a chart speed of 30 inch/hour and the scan speed was set at one degree-two theta per minute. All samples were hand crushed to a -200 mesh size before mounting.

Interpretation and Cell Measurement Studies

Red Garnet. Three (No.'s 14, 17, and 18) diffraction patterns were obtained for the red garnet. From these diffraction patterns, it was indentified as pyrope with the aid of card No. 2-1008 of the X-ray Powder Data File of the ASTM. These patterns were indexed and the results are presented in Table I, in the Appendix. From these data and using the formula,

$$a_o = \frac{\lambda}{2} \frac{\sqrt{h^2+k^2+l^2}}{\sin \Theta} \quad \text{or} \quad a_o = d\mathring{A} \sqrt{h^2+k^2+l^2}$$

as given by Klug (1954), the unit cells were calculated. The unit cell measurements for the different dA spacings are presented in Table II in the Appendix.

The average a_o value obtained from this method was 11.5347 Å. Interpreting this value which corresponds to a larger cell than that for pure pyrope, and based on the index of refraction n=1.747, this garnet falls within the andradite-pyrope-almandite end-members triangle with 75% pyrope and 25% andradite-almandite.

These end member proportions are in disagreement with the interpretation of Troger (1959) based on the chemical analysis of the Stockdale intrusion pyrope by Bagrowski (1941) who reported 7.90% Cr_2O_3 present. The refractive index of a pyrope with this high Cr content should be approximately 1.76 according to Nixon el al (1963) yet is messured as 1.747 (Bagrowski, 1941; and this report). It appears that the Cr content reported by Bagrowski (1941) is too high.

Green Garnet. Nine diffraction patterns were obtained for the green garnet, but only five (No.'s 6,7,8,9 and 10) were used in its interpretation. From the results of indexing these patterns and comparison with ASTM card No. 2-1008, the green garnet was also found to be pyrope. The results are presented in Table III of the Appendix, and the calculations of the unit cell in Table IV, in the Appendix. The unit cell was calculated using the formula given by Klug (1954).

The average a_o value of the green pyrope was found to be 11.5585 Å, slightly larger than that for the red pyrope and even larger than that for pure pyrope.

Based on the unit cell value of 11.5585 Å and the index of refraction of 1.7533, the green garnet was found to be within the andradite-almandite-pyrope end members triangle, consisting of 73% pyrope and 27% andradite-almandite, (Sriramadas, 1957).

Magnetite. Two diffraction patterns of magnetite were studied and indexed. The results, as compared to ASTM card No. 11-614 for magnetite, are presented in Table V, in the Appendix, and the calculation of the unit cell edge in Table VI of the Appendix.

The a_o value was calculated using the same formula for isotropic minerals as given by Klug (1954). The average of this value is 8.3789 Å. According to Deer, Howie and Zussman (1962), this value for a and the specific gravity of 5.13 g/cc, the Stockdale magnetite is between the magnetite-hercynite end members with no magnesioferrite component. According to the same authors, this would correspond to 93.5% magnetite and 6.5% hercynite with some chromium solid solution. The significance of the solid solution between these end members is discussed in a later section of this paper.

Ilmenite. Several mineral mountings were prepated and analyzed by X-ray diffraction which were believed to be chromite. After indexing and correlation with ASTM card 3-0781 they were found to be ilmenite. Several other aliquots of pure ilmenite were also analized, and from both mountings five diffraction patterns were included in this study. The results of the indexing are presented in Table VII of the Appendix.

The calculation of the unit cell of ilmenite, not being an isotropic mineral, was done by the following procedure described by Klug (1954) for hexagonal and rhombohedral minerals. The following formula was used:

$$\log a_o = \log(d\text{Å}) + 1/2 \log 4/3(h^2+hk+k^2) + l^2/c^2$$

where h, k and l are the Miller indices from the diffraction pattern and c is a correction factor as found from Plate IV by matching horizontally the found values for the strong peaks of the diffraction pattern of ilmenite with the curves in the plate which correspond to the same Miller indices of the reflections.

Using the value for c = 2.80 thus determined, a_o was calculated (Table VIII, of the Appendix). The average value for the unit cell is 5.050 Å. The value of c is, in turn, equal to c_o/a_o. From this,

$$c = c_o/a_o$$

$$c_o = c \cdot a_o$$

$$c_o = 2.80 \times 5.050 \text{ Å}$$

$$c_o = 14.140 \text{ Å}$$

The values of a_o = 5.050 Å and c_o = 14.140 Å correspond to hexagonal ilmenite and not to rhombohedral ilmenite as previously believed.

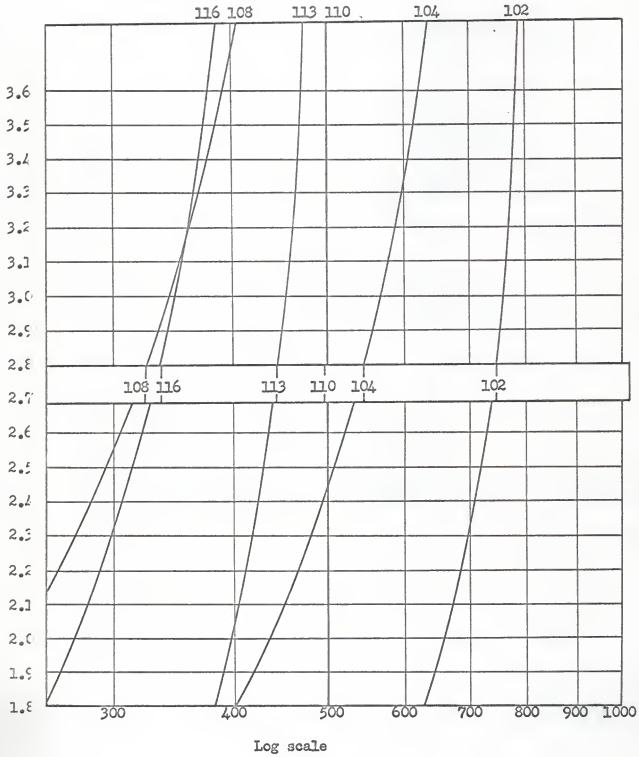
Mica. As previously mentioned, two aliquots were prepared for X-ray diffraction study; one treated with 3N glacial acetic acid to remove the calcite, and another one untreated. This was done in order to study the effects of the presence of calcite in the diffraction pattern of the mica and to determine any effects the acid treatment might have on the mica structure. It was found from their respective patterns that the presence of calcite did not alter the configuration of the mica; and the treatment with acid removed the calcite and weakened the mica structure, as was found later in the heating procedures.

Two diffraction patterns of randomly oriented sample of each aliquot of mica were studied. Most of the peaks indexed corresponded to chlorite. Some residual peaks of very low intensity were recognized to be phlogopite. As

EXPLANATION OF PLATE IV

Calculation of the c correction factor by matching horizontally the found values for the strong peaks of the diffraction pattern of ilmenite with the curves in the plate which correspond to the same Miller indices of the reflections. (After Klug, 1954).

PLATE IV


116 108
113 110
104
102
3.6
3.5
3.4
3.3
3.2
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
108 116
113
110
104
102
300
400
500
600
700
800
900
1000
Log scale
e values

stated before in the microscopic description of the mica, there is evidence that supports this finding.

Three oriented slides were prepared for each aliquot of mica. One slide of each was studied untreated; the same slide was then treated with glycol and X-rayed again. The glycol treatment was found to have only slight effect on the structural configuration of the mica. Only a slight swelling was detected by the shifting of the 14 Å peak. This indicates that the chlorite is not expandable, Brown (1961) and Brindley (1961).

For each aliquot, the remaining two oriented slides were heated for one hour at 450°C and 600°C respectively. The heating at 450°C did not displace most of the peaks but only lowered their intensity. Only the 14 Å peak showed significant change. Two peaks developed in its place, one at 13.84-14.06 Å and one at 9.93 Å. The later persisted after heating at 600°C whereas all other peaks disappeared.

According to Walker (1961), the heating of the specimen in air to successively higher temperatures and allowing it to cool before examination gradually displaces the 14 Å reflection of Mg-vermiculite to 9-10 Å whereas the 14 Å reflection of chlorite remains close to its value. Therefore, the displacement of a 14 Å reflection to the vicinity of 10 Å on heating can not be due to chlorite.

Vermiculite is therefore believed to accompany the chlorite in low proportions. Both, nevertheless, do not occur as interstratified micas otherwise a superlattice of around 28 Å value would be detected (and it is not).

A last oriented slide was prepared for each aliquot of mica after treatment with 12 N vycor distilled hydrochloric acid for 8 hours. Both were X-rayed and the resulting diffraction patterns showed only three peaks of

very low intensity at 14.20-14.29 Å, 7.26-7.27 Å and 3.64, which are interpreted as undissolved chlorite. Brindley (1961) states that dilute hydrochloric acid dissolves many chlorites, particularly when they are fine grained.

Another definite proof of the identity of the chlorite is the fact that, as stated by Brindley (1961) and Brown (1961), after the heating at 450°C the second order line (around 7.1 Å) will be stronger than the first order reflection at 14.2 Å.

Uvarovite Standard. Three diffraction patterns were studied for the purpose of comparison with the garnets present. The results of indexing are presented in Table IX, and the calculation of the a values in Table X, both in the Appendix. The average a. value calculated was 12.0322 Å. The uvarovite was identified by comparison with card No. 11-696 of the ASTM.

Also, by comparison with the green and red pyropes drescribed earlier, no similarities were found between them and the chrome garnet described here.

Silicon Standard. One diffraction pattern was studied for silicon with the purpose of comparing set standards of the X-ray instrument and possible impurities in the samples. The unit cell was not calculated.

Red Garnet Impurities. During the preliminary crushing of the red garnet some of the impurities and alteration products (kelyphitic rims) were separated by size. This separate was analyzed by X-ray and found to be composed of pyrope, calcite, antigorite and others. The sample probably included chrysotile as found petrographically, but because of the lack of an ASTM card for comparison, it was not possible to positively identify it.

AGE DETERMINATION

Two 5 gram samples of chloritized phlogopite were analyzed for Argon and Potassium content by the Geochron Laboratories, Inc., Cambridge, Massachusetts. In the analyses the numbers 80583 and 80585 were assigned to the samples.

The results of these analyses are presented in Table V. The ages were calculated by the following formula:

$$\text{Age} = \frac{1}{\lambda_e + \lambda_a} \ln \left[\frac{\lambda_e + \lambda_a}{\lambda_e} \times \frac{Ar^{40*}}{K^{40}} + 1 \right]$$

using the following constants:

$\lambda_a = 4.72 \times 10^{-10}$/year

$\lambda_e = 0.585 \times 10^{-10}$/year

$K^{40}/K = 1.22 \times 10^{-10}$ g/g

Ar^{40*} refers to radiogenic Ar^{40}

Sample 80583

The age calculated for this sample is $331 \pm 50 \times 10^6$ years. The large error found was attributed to the Potassium analyses which were in poor agreement. The difference between the two analyses can be attributed to inhomogenieties in the samples.

The sample contained some highly chloritized phlogopite portions with very high Potassium content and probably consisted of a mixture of primary phlogopite and some chlorite with virtually no Potassium. This contrast in the Potassium content of the mixture along with the great variation in grain size lead to sampling errors.

The two Argon analyses are not very radiogenic but they give very

EXPLANATION OF TABLE V

Values obtained for the messured Ar^{40*}, Ar^{40} and K^{40}, and the calculated ages.

TABLE V

Sample Number	Argon Analysis	Ar^{40*}/total Ar^{40}	Average Ar^{40*}, ppm	% K	Average % K	K^{40}, ppm	Ar^{40*}/K^{40}	Age
80583	a) 0.00504	0.081	0.00508	a) 0.180	0.197	0.240	0.0212	$331 \pm 50 \times 10^6$y
	b) 0.00511	0.091		b) 0.215				
80585	a) 0.00515	0.314	0.00489	a) 0.44	0.465	0.567	0.0086	$142 \pm 20 \times 10^6$y
	b) 0.00463	0.274		b) 0.49				

Ar^{40*} refers to radiogenic Ar^{40}

excellent reproducibility (see Table V).

Sample 80585

The age for this sample, $142 \pm 20 \times 10^6$ years, is low. The probable cause of this low age and the errors is sampling.

The duplicate analyses for Potassium are higher than in sample 80583, hence the age calculated for sample 80585 is lower.

DISCUSSION

Mineralogical Aspects

Garnets. There are two distinct garnets present in the Stockdale intrusion. These exhibit a complete and continous color variation between deep red and deep green end members. Both of these members have been identified by X-ray analysis as pyrope. Tha small differences in their refractive indices, unit cell messurements, and the d-spacings are shown in Tables I, and III of the Appendix. The variations between the two may indicate a continous range of temperature and pressure conditions during crystallization, (Smirnov, 1959) and (O'Hara and Mercy, 1963).

A uvarovite standard was analyzed for comparison with the green end member (see Table IX, in the Appendix), and the latter was determined not to be uvarovite. Some chromium substitution is probable as evidenced by the high refractive indices found for both pyropes relative to the value of 1.71 for pure, artificial pyrope. Bagrowski (1941) has found a Cr_2O_3 content of 7.90% for the red variety, but this value is possibly too high as according to Nixon et al (1963) the refractive index for this high Cr_2O_3 content should be greater than 1.747.

The upper limit of pressure stability for pyrope is determined by the intersection of the continental geotherm and the graphite-diamond curve (see Plate V, Fig. 1), which corresponds to approximately 40 kilobars. The maximum temperature for the crystallization of pyrope at these pressures is approximately 1200°C (Boyd, 1961). Temperatures as high as 1600°C have been reported in the literature as an upper limit, but at these temperatures the pyrope molecule dissolves very readely in clinopyroxene (O'Hara, 1963) and therefore it will be absent from the rock. The pyropes, based on these pressures and temperature limits probably crystallized before the phlogopite and contemporaneously with the olivine and pyroxenes.

Magnetite. The unit cell messurement of magnetite is 8.3789 Å. This value is somewhat lower than the 8.3963 calculated for pure magnetite (ASTM card No. 11-614). This different value for a could be explained by solid solutions of magnetite with other members of the magnetite series: 1. magnesioferrite, even if it has a smaller unit cell, cannot be the cause of this decrease because low percentage solid solution with magnetite actually enlarges the unit cell (Deer, Howie and Zussman, 1962); 2. chromite solid solution would also enlarge the unit cell of magnetite; 3. ulvospinel and jacobsite have larger unit cells messurements and therefore could not be responsible for the decrease noted; 4. hercynite solid solution with magnetite is the most probable explanation for the decrease in a_o. This is consistent with the low specific gravity messured.

Serpentinization would be the only process by which enough alumina would be liberated for the hercynite to form in the alumina-deficient environment where alteration and crystallitation of magnetite occurred. Based on these assumptions, magnetite is secondary. This would indicate that serpentiniza-

tion occurred prior to final emplacement. This is also consistent with the inferred low content of magnesium in the magnetite.

Ilmenite. Chayes (1964) and Chayes and Velde (1965) showed that TiO_2 is by far the most useful single oxide in distinguishing between intraoceanic and circumoceanic cenozoic basalts. In this view, MacGregor (1965) states that:

"With increasing pressure the TiO_2 content increases and the MgO/SiO_2 ratio decreases from 1 to 10 kilobars and increases from 10 to 20 kilobars. No data is available for pressures in excess of 20 kilobars but pressuming a linear extrapolation, minimum melts at 30 kilobars and greater would be more titaniferous".

He also notes that:

"If the trends found in the ternary $MgO-SiO_2-TiO_2$ may be projected into and valid for the more complex system, however, it would indicate that the TiO_2 content of a basalt may be significantly dependent on pressure".

This same reasoning applies to peridotites.

The smaller unit cell of ilmenite as compared with the ASTM standard ilmenite card No. 3-0781 indicates some solid solution of MgO in the structure. This solid solution, in turn, indicates a deeper crystallization than 20-30 kilobars which together with the low ferric iron content seem to be consistent with the other present work.

Carbonates. At least two generations of carbonate mineralization are recognized in the Stockdale intrusion. By petrographic evidence it was found that some of the mica had been replaced by calcareous material which was formed after the original crystallization of the mica and probably prior to final emplacement.

This calcareous material is evidence for the presence of abundant carbon dioxide in the system (Bailey, 1964). These veinlets of primary calcareous

material are cut by possible post-emplacement calcite veins. The secondary calcite veins also show evidence of multireplacement probably caused by ground water deposition.

Other Chemical Considerations. Sperry (1929) has presented a chemical analysis of the Stockdale intrusion. This analysis plus others are presented in Table VI.

It is obvious that the high percentage of CaO and CO_2 in the Stockdale intrusion is primarily due to xenocrysts of calcite, inclusions of calcareous country rock, and secondary calcite. The high concentrations of these two oxides modify the percentages of all other oxides analyzed, which otherwise would be higher an closer to the average values of oxide concentrations in kimberlites presented by Nockolds (1954).

Reducing the CaO and CO_2 percentages to 6.80% and 2.15% respectively (average values from Nockolds' analyses), the remaining percentages were recalculated for the other oxides. These new values are presented in column No. 4, Table VI. These values are closer to those for kimberlites and therefore it is concluded that the Stockdale intrusion is kimberlitic in composition and that the minor variations noted are due to local formational and injection events.

Petrogenetic Aspects

Field relationships of the Stockdale intrusion show that the rock has been intruded as a low temperature, largely crystalline mass due to tectonic forces. The doming effects observed over other intrusion bodies in Riley County, Kansas, is indicative of forced intrusion.

The probable time of final emplacement of the Stockdale intrusion was

Table VI Chemical analyses of some kimberlites

Oxide	1	2	3	4
SiO_2	35.02	36.33	24.15	29.47
TiO_2	1.22	1.89	1.50	1.83
Al_2O_3	3.90	5.09	2.03	2.47
Cr_2O_3	-	-	-	-
Fe_2O_3	5.15	7.43	6.51	7.94
FeO	4.14	3.40	1.85	2.26
MnO	0.06	0.10	-	-
MgO	31.29	26.63	24.45	29.84
CaO	6.80	6.78	15.87	6.80
Na_2O	0.34	0.37	-	-
K_2O	1.05	2.43	0.30	0.37
H_2O^+	7.43	7.25	8.50	10.37
H_2O^-	-	-	0.85	1.04
P_2O_5	0.87	0.66	0.62	0.76
CO_2	2.73	1.64	12.04	2.18
SO_3	-	-	0.20	0.24
Total	100.00	100.00	98.87	95.57

1. Average chemical composition of basaltic kimberlite, 10 analyses (Nockolds, 1954).

2. Average chemical composition of micaceous kimberlite, 4 analyses (Nockolds, 1954).

3. Chemical analysis of the Stockdale intrusion (Sperry, 1929).

4. Corrected chemical analysis of the Stockdale intrusion based on CaO and CO_2 percentages of 6.80 and 2.18 respectively.

Late Cretaceous (Byrne, Parish and Crumpton, 1956). The ages obtained by the Potassium-Argon method (see Table V) on the chloritized phlogopite indicate then that most of the primary crystallization occurred before final emplacement. The fact that the dates obtained from the mica are older than the time of intrusion also indicates a very low temperature of intrusion, as otherwise the Argon would have been lost by thermal diffusion and the ages calculated would be younger. The temperature of intrusion might have been as low as 200°C.

The absence of spinel in the rock as primary mineral indicates that the original magma crystallized in the pyrope-forsterite stability field (see Plate V, Fig. 1). This, in turn, indicates a deeper zone of original crystallization, probably around 65-95 kilometers deep or 21 to 30 kilobars of pressure.

The absence of spinel as a secondary mineral or as an alteration-inversion product of pyrope indicates a final crystallization temperature greater than 465°C and at an approximate pressure of 12 kilobars, (see Plate V, Fig. 1). This lower pressure and temperature might have resulted from the upward movement of the crystallizing body through the upper mantle and lower crust.

The presence of a hydrous phase, chlorite, allows estimation of a minimum temperature of formation which restricts even more the original crystallization conditions,(see Plate VI). This temperature can be interpolated from Plate VI to be around 900-1000°C maximum, which according to Fig. 1 of Plate V corresponds to a minimum pressure of approximately 20 Kilobars.

The evidence of high abundance of carbon dioxide in the system as presented in the mineralogical aspects of this discussion, would indicate a lower temperature and a higher pressure for the crystallization of the mica (Bailey, 1964).

EXPLANATION OF PLATE V

Fig. 1. Phase-equilibria data combined with geotherms for oceanic areas (A) and Precambrian shields (B). (After a composite diagram by Boyd and MacGregor, 1964, including information from Ringwood, 1964, Boyd and England, 1961, MacGregor, 1964 and Bundy, Bovenkerk, Strong and Wentrof, 1961).

Fig. 2. Speculative section of the crust and upper mantle extending from a Precambrian shield to an oceanic region. (After Boyd and MacGregor, 1964).

PLATE V

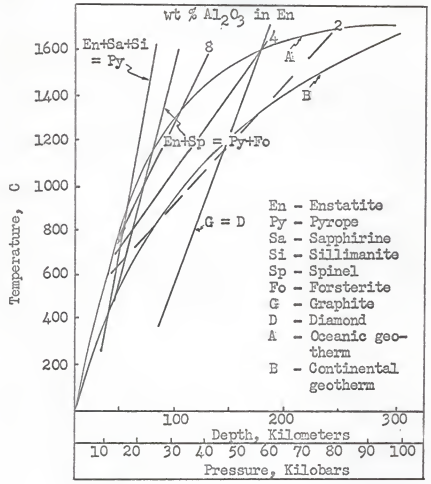


Fig. 1

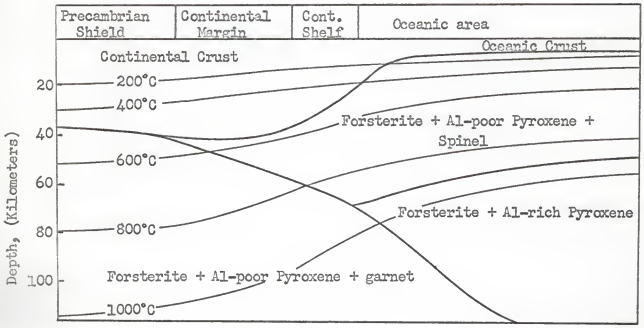
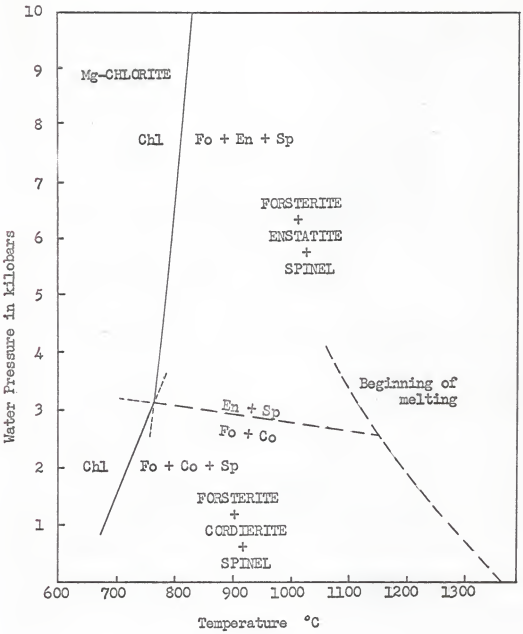


Fig. 2

EXPLANATION OF PLATE VI

The upper stability limits of the magnesian chlorites to 10 kb P_{H_2O}. (After a composite diagram by Fawcett, 1964 including information from Mervin, 1918 and Yoder, 1952.

PLATE VI


Mg-CHLORITE
Chl
Fo + En + Sp
FORSTERITE
+
ENSTATITE
+
SPINEL
Beginning of
melting
En + Sp
Fo + Co
Chl
Fo + Co + Sp
FORSTERITE
+
CORDIERITE
+
SPINEL
Water Pressure in kilobars
Temperature °C
10
9
8
7
6
5
4
3
2
1
600
700
800
900
1000
1100
1200
1300

The garnet is represented by two pyropes which exhibit a complete range of color variation between the red and the green end members. Very fine shades form gradational transitions between them. This crystallization indicates a complete and continous range of temperatures and pressures of formation.

The presence of calcareous replacement of the chloritized phlogopite indicate the generation of a gas phase rich in water and carbon dioxide (O'Hara and Mercy, 1963).

Emplacement probably occurred at a temperature as low as 200°C and at a pressure equal to the local lithostatic load which probably did not exceed one kilobar. The lack of disturbance in the country rock near and around the intrusion indicate that the Stockdale intrusion was not emplaced by the pushing aside of the country rock but has been controlled by the pre-exhisting joint patterns. Carbon dioxide and residual water probably served as the lubricating mechanism during injection.

The joint systems of the Permian and Cretaceous rocks are not present in the Stockdale intrusion. This fact, together with other field evidence presented by Byrne et al (1956), indicate that the time of intrusion was Late Cretaceous.

After final emplacement, the last step in the sequence of events was the fracturing and jointing of the rock, which resulted from the contraction during cooling. Subsequent deposition of calcite in the openings by ground water followed.

The rock, as a whole, can be described as a serpentinized peridotite, and more properly as a kimberlite.

CONCLUSIONS

Based on all the data obtained during this investigation and on the discussion presented in the preceeding section, the following conclusions are in order:

1. There are two garnets, one green and one red, present and both are pyrope. Slight differences in the unit cell messurements and index of refraction are attributed to different percentages of andradite-almandite and pyrope end members.

2. The magnetite is secondary.

3. The ilmenite is primary. This mineral was of the first minerals to crystallize from the original magma.

4. The original crystallization included the formation of olivine, pyroxene, ilmenite and the garnets.

5. After the begining of the formation of olivine, pyroxene and ilmenite the pyropes continued to crystallize contemporaneously with them at a range between 20 and 30 kilobars of pressure and between 800°C and 1200°C.

6. The phlogopite crystallized after the pyropes.

7. The chloritization of the primary mica occurred after the first stages of crystallization. Replacement of the mica by chlorite and carbonate material followed.

8. Serpentinization occurred before emplacement.

9. Most of the magnetite formed as secondary mineral after and during the serpentinization of the olivines and pyroxenes.

10. The Stockdale intrusion was emplaced as a result of tectonic forces.

11. Injection occurred through zones of weakness in the crust along joints ological anomalies in the crust.

12. The rock was intruded in a "mush-like" state with carbon dioxide and residual water as lubricating agents at a very low temperature.

13. The joints and fractures in the intrusion, post-Cretaceous in age, are the result of cooling and shrinking after emplacement, and not of the joint systems in the surrounding country rock which are Permian and Cretaceous in age.

14. There has not been any mineralization of the intrusion since emplacement other than the deposition of calcite by ground water in contraction openings and in the post-Cretaceous joints.

15. The Stockdale intrusion may be classified as a garnetiferous micaceous serpentinized peridotite (or kimberlite).

In addition, the following statements probably also apply:

1. The content of hercynite in solid solution causes the smaller a value and lower specific gravity noted in the magnetite.

2. The temperature of intrusion might have been as low as 200°C.

3. The crystallization of the Stockdale intrusion probably started at temperatures higher than 1200°C and at a pressure in excess of 30 kilobars.

4. Emplacement occurred during Late Cretaceous time.

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APPENDIX

EXPLANATION OF TABLE I

ASTM dA spacings and corresponding hkl as compared to three diffraction patterns of the red pyrope.

TABLE I

hkl	941	664	842	840	811	800	642	640	444	620	611	440	521	510	422	332	420	400
ASTM dÅ	1.16	1.23	1.26	1.29	1.42	1.44	1.54	1.60	1.66	1.82	1.87	2.03	2.10	2.26	2.35	2.46	2.58	2.88
14.- dÅ	-	-	1.25	1.29	-	-	1.54	1.60	1.67	-	1.87	2.04	2.11	2.27	2.36	2.47	2.58	2.88
Int.	-	-	v.w*	w.*	-	-	m.*	w.	w.	-	w.	w-m.	w.	w-m.	w-m.	m.	v.s*	s.*
17.- dÅ	1.16	1.23	1.26	1.29	-	1.44	1.54	1.60	1.66	1.82	1.87	-	2.11	2.26	2.36	2.46	2.57	2.88
Int.	vw-w	w.	w.	w.	-	vw-w	vs.	m.	m-w.	w.	m-s.	-	m.	m.	s.	m.	vvs.	vs.
18.- dÅ	-	1.23	1.26	1.29	1.42	1.44	1.54	1.60	1.66	1.82	1.87	-	2.11	2.26	2.35	2.46	2.58	2.89
Int.	-	vw-w	m.	w.	vw-w	w-m.	m.	s.	m-s.	m.	m.	-	m.	m.	s.	m.	vs.	vs.
Average dÅ	1.16	1.23	1.26	1.29	1.42	1.44	1.54	1.60	1.66	1.82	1.87	2.04	2.11	2.26	2.36	2.46	2.58	2.89
Int.	vw-w	w.	w.	w.	vw-w	w.	m-s.	m.	m.	w-m.	m.	w-m	m.	m.	s.	m.	vs.	vs.

v.w* indicates very weak; w.* indicates weak; m.* indicates medium; s.* indicates strong; and v.s.* indicates very strong.

EXPLANATION OF TABLE II

The calculation of a values for each dA spacing and the average a value for red pyrope.

TABLE II

hkl	$d\mathring{A}$	$m = h^2+k^2+l^2$	$\sqrt{m}$	a_o
400	2.89	16	4.0000	11.5600
420	2.58	20	4.4721	11.5381
332	2.46	22	4.6904	11.5384
422	2.36	24	4.8990	11.5616
510	2.26	26	5.0990	11.5238
521	2.11	30	5.4772	11.5570
611	1.87	38	6.1644	11.5274
620	1.82	40	6.3246	11.5107
444	1.66	48	6.9282	11.5008
640	1.60	52	7.2111	11.5378
642	1.54	56	7.4833	11.5243
800	1.44	64	8.0000	11.5200
840	1.29	80	8.9443	11.5381
842	1.26	84	9.1652	11.5481

Summation of a_o's = 161.4861

Average a_o = 161.4861/14 = 11.5347

EXPLANATION OF TABLE III

ASTM dA spacings and corresponding hkl as compared to five diffraction patterns of green pyrope.

TABLE III

hkl	664	921	840	800	642	640	444	620	611	521	510	422	332	420	400
ASTM dÅ	1.23	1.26	1.29	1.44	1.54	1.60	1.67	1.84	1.88	2.11	2.27	2.36	2.46	2.58	2.90
6.- dÅ	1.23	1.26	1.29	1.43	1.54	1.60	1.67	1.83	1.87	2.11	2.26	2.36	2.46	2.58	2.89
Int.	w.*	m.*	w.	m.	s.*	m.	w.	w.	m.	m.	m-s.	s.	m.	s.	vvs*
7.- dÅ	-	1.26	1.30	-	1.55	1.61	1.67	1.83	1.88	2.11	2.27	2.37	2.47	2.59	2.90
Int.	-	m.	s.	-	vvs.	m-s.	vw.*	w.	m-s.	m.	s.	m.	s.	vvs.	m-s.
8.- dÅ	1.23	1.26	1.29	1.44	1.54	1.60	1.67	1.83	1.89	2.11	2.27	2.36	2.47	2.59	2.90
Int.	m.	m.	w.	m.	vs.*	s.	w-m.	w.	m.	m.	m.	s.	m.	m-s.	m.
9.- dÅ	1.23	1.26	1.29	1.45	1.55	1.60	-	1.83	1.88	2.11	2.27	2.37	2.47	2.59	2.90
Int.	w-m.	m.	w.	m-s.	vs.	m.	-	vw.	s.	m.	m.	m-s.	m.	vs.	m-s.
10.- dÅ	-	1.26	-	-	1.54	1.60	1.67	1.83	1.87	2.11	2.27	2.36	2.46	2.58	2.90
Int.	-	w.	-	-	m-s.	m.	m.	w.	m.	m.	s.	m-s.	m.	vs.	s.
Average dÅ	1.23	1.26	1.29	1.44	1.54	1.60	1.67	1.83	1.88	2.11	2.27	2.36	2.47	2.59	2.90
Int.	m.	m.	w-m.	m.	s.	m.	w-m.	w.	m-s.	m.	m-s.	m-s.	m.	vs.	m-s.

vw* indicates very weak; w.* indicates weak; m.* indicates medium; s.* indicates strong; vs.* indicates very strong; vvs.* indicates very very strong.

EXPLANATION OF TABLE IV

The calculation of a values for each dA spacing and the average a value for green pyrope.

TABLE IV

hkl	dÅ	$m = h^2+k^2+l^2$	$\sqrt{m}$	a_o
400	2.90	16	4.0000	11.5920
420	2.59	20	4.4721	11.5828
332	2.47	22	4.6704	11.5360
422	2.36	24	4.8989	11.5614
510	2.27	26	5.0990	11.5646
521	2.11	30	5.4772	11.5570
611	1.88	38	6.1644	11.5768
640	1.60	52	7.2111	11.5538
642	1.54	56	7.4833	11.5542
800	1.44	64	8.0000	11.5200
840	1.29	80	8.9443	11.5649
664	1.23	88	9.3808	11.5384

Summation of a_o's = 138.7018

Average a_o = 138.7018/12 = 11.5585

EXPLANATION OF TABLE V

ASTM dA spacings and corresponding hkl as compared to two diffraction patterns of magnetite.

EXPLANATION OF TABLE VI

The calculation of a values for each dA spacing and the average a value for magnetite.

TABLE V

hkl		533	440	511	422	400	311	220	111
ASTM	dÅ	1.28	1.48	1.61	1.71	2.10	2.53	2.97	4.85
15.-	dÅ	-	1.48	1.61	1.71	2.10	2.53	2.96	4.83
	Int.	-	m.	m.	w.	w.	s.	w.	vw.
16.-	dÅ	1.28	1.48	1.61	1.71	2.09	2.53	2.97	-
	Int.	vw.	w.	w.	m.	m.	s.	w.	-
Average	dÅ	1.28	1.48	1.61	1.71	2.10	2.53	2.97	4.83
	Int.	vw.	m-w.	w-m.	w-m.	w-m.	s.	w.	vw.

TABLE VI

hkl	dÅ	$m = h^2+k^2+l^2$	$\sqrt{m}$	a_o
111	4.83	3	1.7321	8.3658
220	2.97	8	2.8284	8.3863
311	2.53	11	3.3166	8.3911
400	2.10	16	4.0000	8.3800
422	1.71	24	4.8990	8.3773
511	1.61	27	5.1962	8.3658
440	1.48	32	5.6569	8.3721
533	1.28	43	6.5574	8.3935

Summation of a_o's = 67.0318

Average a_o = 8.3790

EXPLANATION OF TABLE VII

ASTM dÅ spacings and corresponding hkl as compared to five diffraction patterns of ilmenite.

TABLE VII

hkl		226	314	2010	312	220	1010	300	214	108	116	204	113	110	104	102
ASTM	dÅ	1.12	1.15	1.18	1.20	1.27	1.34	1.47	1.50	1.63	1.72	1.86	2.23	2.54	2.74	3.73
1.-	dÅ	1.10	1.15	1.18	-	1.28	1.33	1.46	1.52	1.62	1.71	1.86	2.23	2.53	2.73	3.72
	Int.	vw.	vw.	vw.	-	vw.	w.	w.	w.	vw.	s.	m.	m.	s.	vs.	s.
2.-	dÅ	-	1.15	1.18	1.20	-	1.33	1.46	1.52	1.62	1.70	1.87	2.22	2.53	2.73	3.71
	Int.	-	vw.	vw.	vw.	-	w.	w.	w.	vw.	vs.	m.	m.	s.	vvs.	m-s.
3.-	dÅ	1.11	1.15	1.18	1.20	1.27	1.32	1.42	1.52	1.62	1.71	1.86	2.23	2.53	2.73	3.71
	Int.	vw.	vw.	w.	vw.	w.	w.	m.	vw.	vw.	s.	s.	m-s.	s.	vs.	s.
4.-	dÅ	-	1.15	-	1.20	1.27	1.32	1.46	1.52	1.62	1.71	1.86	2.23	2.53	2.73	3.71
	Int.	-	vw.	-	vw.	vw.	s.	m.	m.	w.	s.	m.	s.	s.	vs.	s.
5.-	dÅ	1.13	1.15	-	-	1.27	1.33	1.46	1.50	1.62	1.71	1.86	2.22	2.53	2.73	3.72
	Int.	w.	vw.	-	-	vw.	w.	w-m.	m.	vw.	m.	m.	s.	s.	s.	m-s.
Average	dÅ	1.11	1.15	1.18	1.20	1.27	1.32	1.46	1.52	1.62	1.71	1.86	2.23	2.53	2.73	3.71
	Int.	vw.	vw.	vw-w	vw.	vw.	w-m.	w-m.	w.	vw.	s.	m.	m-s.	s.	vs.	s.

EXPLANATION OF TABLE VIII

The calculation of a values for each dA spacing, and the average a value for ilmenite.

TABLE VIII

hkl	dÅ	log dÅ	$m=4/3(h^2+hk+k^2)+l^2/c^2$	1/2log m	log a_o	a_o
102	3.714	0.56984	1.843	0.13276	0.70230	5.039
104	2.730	0.43616	2.041	0.26407	0.70023	5.015
110	2.530	0.40312	4.000	0.30103	0.70415	5.060
113	2.226	0.34753	5.148	0.35582	0.70335	5.051
204	1.862	0.27035	7.374	0.43385	0.70406	5.059
116	1.708	0.23249	8.592	0.46704	0.69953	5.007
214	1.516	0.18041	11.374	0.52795	0.70836	5.109
300	1.460	0.16435	12.000	0.53959	0.70394	5.058

Summation of a_o's = 40.398

Average a_o = 5.050

$c = c_o/a_o$ - $c_o = c.a_o$

c_o = 5.050 x 2.8 = 14.140

EXPALNATION OF TABLE IX

ASTM dA spacings and corresponding hkl as compared to three diffraction patterns of uvarovite.

TABLE IX

hkl	10.4.2	10.4.0	842	840	800	642	640	444	620	611	621	431	422	332	420	400	220
ASTM dÅ	1.10	1.11	1.31	1.34	1.50	1.60	1.66	1.73	1.90	1.95	2.19	2.35	2.45	2.56	2.68	2.99	4.24
11.- dÅ	1.10	1.12	1.31	1.34	1.50	1.61	1.67	1.73	1.90	1.95	2.20	2.36	2.45	2.58	2.69	3.01	4.25
Int.	w.	w-m.	w.	w.	vw.	s.	m.	w-m.	w-m.	m.	m.	m.	s-vs	vs.	vs.	m.	m.
12.- dÅ	1.10	1.12	1.31	1.34	1.50	1.61	1.67	1.74	1.90	1.95	2.20	2.36	2.45	2.56	2.68	3.01	4.26
Int.	w.	w.	w-m.	w.	vw.	s.	m.	vw-w	w.	m.	w-m.	w-m.	m-s.	w.	vs.	s.	w-m.
13.- dÅ	1.10	1.12	1.31	1.34	1.50	1.61	1.67	1.74	1.90	1.95	2.20	2.36	2.45	2.56	2.69	3.00	4.26
Int.	m.	w.	w.	w.	vw.	s.	m.	w.	w.	m.	w-m.	w-m.	s.	w.	vs.	vvs.	w-m.
Average dÅ	1.10	1.12	1.31	1.34	1.50	1.61	1.67	1.74	1.90	1.95	2.20	2.36	2.45	2.57	2.69	3.01	4.26
Int.	w-m.	w.	w.	w.	vw.	s.	m.	w.	w.	m.	w-m.	w-m.	s.	m.	vs.	s.	w-m.

EXPLANATION OF TABLE X

The calculation of a values for each dA spacing, and the average a value for uvarovite.

TABLE X

hkl	dÅ	$m=h^2+k^2+l^2$	$\sqrt{m}$	a_o
220	4.26	8	2.8284	12.0491
400	3.01	16	4.0000	12.0400
420	2.69	20	4.4721	12.0300
332	2.57	22	4.6904	12.0544
422	2.45	24	4.8990	12.0025
431	2.36	26	5.0990	12.0337
621	2.20	30	5.4772	12.0499
611	1.95	38	6.1644	12.0206
620	1.90	40	6.3246	12.0167
444	1.74	48	6.9282	12.0551
640	1.67	52	7.2111	12.0425
642	1.61	56	7.4833	12.0481
800	1.50	64	8.0000	12.0000
840	1.34	80	8.9443	11.9353
842	1.31	84	9.1652	12.0064
10.40	1.12	116	10.7703	12.0628
10.42	1.10	120	10.9545	12.0499

Summation of a_o's = 204.5469

Average a_o = 204.5469/17 = 12.0321

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MINERALOGY AND PETROGENESIS OF THE STOCKDALE INTRUSION, RILEY COUNTY, KANSAS

by

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ABSTRACT

Five igneous intrusions are known to occur in Riley County, Kansas. Of these, the Stockdale intrusion was studied in this investigation.

The intrusion was first mapped in detail. Samples were then collected in the field for laboratory study by X-ray diffraction, index of refraction, and gravity measurements.

The rock samples were crushed and sieved, and pure mineral aliquots were separated for examination. In this manner, red and green garnets, chloritized phlogopite, ilmenite and magnetite were purified and prepared for X-ray study. Both garnets were identified as pyrope; and the chloritized phlogopite was found to consist primarily of chlorite with minor amounts of primary phlogopite and vermiculite. Magnetite and ilmenite were positively identified in the same manner.

Unit cell dimensions were calculated for the pyropes (green, a_o= 11.5585; red, a_o= 11.5347), ilmenite (a_o= 5.050, c_o= 14.140), and magnetite (a_o= 8.3790); and a uvarovite standard (a_o= 12.0321) was analyzed for comparison with the pyropes.

The petrogenetic aspects of this study indicate a primary crystallization of red pyrope, pyroxene, olivine and ilmenite at approximately 40 kilobars pressure and 1200°C. This corresponds to an original source region in the upper mantle. Crystallization continued for the pyrope until lower temperatures and pressures permited the crystallization of the original phlogopite. The mica was then later chloritized and partially replaced by dolomitic carbonate.

Serpentinization probably occured during the early injection history but before final emplacement. In addition to serpentine, magnetite was

the principal secondary mineral that crystallized concurrent with or immediately after serpentinization as indicated by its low unit cell value. In addition, many of the inclusions of the country rock material have not been chloritized.

Potassium-Argon ages of 331 $\pm$ 50 million years and 142 $\pm$ 20 million years on the chloritized phlogopite also confirm that the alteration was pre-emplacement as the geologic age of the final emplacement of the Stockdale intrusion is Late Cretaceous which corresponds to 80 to 100 million years. Because of the preservation of this pre-emplacement Argon an upper limit of the temperature of injection can be placed at 150°C to 200°C.

Fracturing and jointing occurred during and post-emplacement, and these openings have been filled by ground water deposited calcite. This was the last pre-Quaternary event affecting the intrusion.